

X-ray Spectral Variation of η Car through the 2003 X-ray Minimum

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ABSTRACT

We report the results of an X-ray observing campaign on the massive, evolved star η Car, concentrating on the 2003 X-ray minimum as seen by the *XMM-Newton* observatory. These are the first spatially-resolved X-ray monitoring observations of the stellar X-ray spectrum during the minimum. The hard X-ray emission, believed to be associated with the collision of η Car's wind with the wind from a massive companion star, varied strongly in flux on timescales of days, but not significantly on timescales of hours. The lowest X-ray flux in the 2 – 10 keV band seen by *XMM-Newton* was only 0.7% of the maximum seen by *RXTE* just before the X-ray minimum. In the latter half of the minimum, the flux increased by a factor of 5 from the lowest observed value, indicating that the X-ray minimum has two states. The slope of the X-ray continuum above 5 keV did not vary in any observation, which suggests that the electron temperature of the hottest plasma associated with the stellar source did not vary significantly at any phase. Through the minimum, the absorption to the stellar source increased by a factor of 5 – 10 to $N_{\text{H}} \sim 3\text{--}4 \times 10^{23} \text{ cm}^{-2}$. The thermal Fe XXV emission line showed significant excesses on both the red and blue sides of the line outside the minimum and exhibited an extreme red excess during the minimum. The Fe fluorescence line at 6.4 keV increased in equivalent width from 100 eV outside the minimum to 200 eV during the minimum. The small equivalent widths of the Fe fluorescence line suggests small fluorescence yield in the companion's low-density wind. The lack of variation in the plasma temperature is consistent with the eclipse of the X-ray plasma during the minimum, perhaps by a clumpy wind from the primary star, although the deformation of the Fe XXV profile and the relatively weak fluorescence Fe line intensity during the minimum may suggest an intrinsic fading of the X-ray emissivity. The drop in the colliding wind X-ray emission revealed the presence of an additional X-ray component which exhibited no variation on timescales of weeks to years. This new component has relatively cool temperature ($kT \sim 1$ keV), moderate N_{H} ($\sim 5 \times 10^{22} \text{ cm}^{-2}$), large intrinsic luminosity ($L_{\text{X}} \sim 10^{34} \text{ ergs s}^{-1}$) and a size $\lesssim 1''$ (2300 AU at 2.3 kpc). This component may be produced by the collision of high speed outflows at $v \sim 1000\text{--}2000 \text{ km s}^{-1}$ from η Car with ambient gas within a few thousand AU from the star.

Subject headings: Stars: individual (η Car) — stars: early-type — stars: winds, outflows — binaries: general — X-rays: stars

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1. Introduction

η Car is a violently unstable, extremely luminous object and a key tracer of evolution of stars in the upper portion of the Hertzsprung-Russell diagram (Davidson & Humphreys 1997). The star is believed to have had an initial mass of $\gtrsim 150 M_{\odot}$ (Hillier et al. 2001). It is currently in a short, poorly understood evolutionary stage, known as the Luminous Blue Variable (LBV) phase, which is thought to occur near the onset of pulsational instabilities. It provides a convenient laboratory to study how extremely luminous, massive stars evolve and how they shape their environments both geometrically and chemically.

η Car is best known for an extraordinarily powerful eruption in 1843 which sent $\sim 12 M_{\odot}$ (Smith et al. 2003b) of its atmosphere into space, creating a beautiful bipolar nebulosity called the Homunculus around the star. η Car also had a minor eruption in 1890, which produced a small bipolar nebula inside the Homunculus nebula (the “Little Homunculus”, Ishibashi et al. 2003). The star still exhibits a strong mass loss (10^{-4} – $10^{-3} M_{\odot} \text{ yr}^{-1}$ Davidson et al. 1995; Cox et al. 1995; Ishibashi et al. 1999; Hillier et al. 2001; Pittard & Corcoran 2002), preferentially in the polar direction (Smith et al. 2003a; van Boekel et al. 2003). The ejecta and the stellar wind are rich in helium and nitrogen and depleted in oxygen and carbon (Verner et al. 2005; Davidson et al. 1984; Hillier et al. 2001), consistent with CNO processing. Davidson et al. (2005) and Martin & Koppelman (2004) suggested from the change of $H\alpha$ and $H\beta$ line profiles and the increase of optical brightness that η Car is changing rapidly at the present time.

The past decade has witnessed an important change in our understanding of the star. This began with the recognition that the strength of some narrow emission lines, notably He I 10830 Å, vary predictably with a period of 5.52 years (Damineli 1996). Along with observations in infrared (Whitelock et al. 1994; Feast et al. 2001), *mm* (Cox et al. 1995), *cm* (Duncan et al. 1995), and optical (van Genderen et al. 1999)

wavelengths, observations of the X-ray emission from the star have played a key role. *ROSAT* observations in 1992 first showed a variation which appeared to be correlated with Damineli’s emission line variations (Corcoran et al. 1995), and subsequently the 2 – 10 keV lightcurve of the star obtained by *RXTE* (Ishibashi et al. 1999) showed in detail the X-ray variation culminating in a swift, unstable rise to maximum and steep fall to minimum lasting for ~ 3 months, i.e. the same time interval as Damineli’s spectroscopic minimum. These observations clearly show that the star varies in a fundamental way every 5.54 years, and strongly suggest that η Car is two stars, not one. In this binary model, most of the dramatic, pan-chromatic changes are now believed to be produced by the interaction of the UV flux and wind from a companion star with the wind of η Car. Variations in the X-ray region are produced by a wind-wind collision (WWC) of the wind from η Car with the wind of the companion star. A current guess at the system parameters describes a massive hot companion with $M_c \sim 30 M_{\odot}$ plus a brighter primary star with $M_p \gtrsim 80 M_{\odot}$ in a highly eccentric ($e > 0.9$), 5.54 year orbit (Corcoran et al. 2001a, see also Davidson 1999).

During the 1997/98 X-ray minimum, η Car was the target of every available X-ray observatory, including *RXTE* (Ishibashi et al. 1999; Corcoran et al. 2001a), *ASCA* (Corcoran et al. 2000), and *BeppoSAX* (Viotti et al. 2002). The *ASCA* satellite detected hard X-ray emission from η Car (Corcoran et al. 2000), which was characterized by slightly smaller N_H than the pre-minimum state with reduced plasma emission measure (*E.M.*). The limited spatial resolution of *ASCA*, however, left the possibility that the observed emission was due to contamination by unresolved nearby sources. The *BeppoSAX* satellite observed η Car just after the recovery of the X-ray emission (Viotti et al. 2002). The spectrum showed strong absorption of $N_H \sim 1.5 \times 10^{23} \text{ cm}^{-2}$ unlike the *ASCA* spectrum during the minimum, which had an $N_H \sim 3 \times 10^{22} \text{ cm}^{-2}$. The overall X-ray brightness variations observed with *RXTE* are explained well with the colliding wind mechanism (Pittard et al. 1998; Pittard & Corcoran 2002). However, key properties of the X-ray lightcurve were still poorly understood: dramatic changes in X-ray flux as the emission increases to maxi-

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TABLE 1
LOGS OF THE *XMM-Newton* AND *Chandra* OBSERVATIONS

Abbr.	Seq. ID	Observation Start		Exposure (ksec)	Observation Mode	Filter
		Date	ϕ_{orbit}			
Before the minimum						
XMM000726 ^a	112580601	2000 Jul. 26, 06:01 (M2)	0.470	... / ... / 29.6	PFW/PFW/PSW	thick
XMM000728 ^a	112580701	2000 Jul. 28, 00:51 (M2)	0.471	... / ... / 7.8	PFW/PFW/PSW	thick
XMM030125 ^b	145740101	2003 Jan. 25, 13:03 (PN)	0.922	4.8/ ... / ...	PSW/PFW/PFW	thick
XMM030127A ^b	145740201	2003 Jan. 27, 01:08 (PN)	0.922	4.8/ ... / ...	PSW/PFW/PFW	thick
XMM030127B ^b	145740301	2003 Jan. 27, 20:42 (PN)	0.923	4.7/ ... / ...	PSW/PFW/PFW	thick
XMM030129 ^b	145740401	2003 Jan. 29, 01:45 (PN)	0.923	5.8/ ... / ...	PSW/PFW/PFW	thick
XMM030130 ^b	145740501	2003 Jan. 30, 00:00 (PN)	0.924	4.8/ ... / ...	PSW/PFW/PFW	thick
XMM030608	160160101	2003 Jun. 08, 13:31 (M1)	0.988	22.1/27.6/ ...	PSW/PSW/PFW	thick
XMM030613	160160901	2003 Jun. 13, 23:52 (M1)	0.990	21.9/30.4/ ...	PSW/PSW/PFW	thick
During the minimum						
CXO030720 ^c	200216	2003 Jul. 20, 01:47	1.008	90.3	ACIS-S w/HETG	...
XMM030722 ^c	145780101	2003 Jul. 22, 01:51 (M2)	1.009	5.8/8.2/8.4	PSW/PSW/PFW	thick
XMM030802	160560101	2003 Aug. 02, 21:01 (M2)	1.015	12.2/17.1/17.5	PSW/PSW/PFW	thick
XMM030809	160560201	2003 Aug. 09, 01:44 (M2)	1.018	8.7/12.3/12.6	PSW/PSW/PFW	thick
XMM030818	160560301	2003 Aug. 18, 15:23 (M2)	1.023	13.0/18.2/18.6	PSW/PSW/PFW	thick
CXO030828	200237	2003 Aug. 28, 17:38	1.028	18.8	ACIS-S	...
After the minimum						
CXO030926	200217	2003 Sep. 26, 22:47	1.042	70.1	ACIS-S w/HETG	...

NOTE.—Abbr.: abbreviation adopted for each observation. Seq. ID: sequence identification number of each observation. Observation Start Date: start time of the detector in the parentheses. $\phi_{orbit} = (\text{JD}[\text{observation start}] - 2450799.792)/2024$ (Corcoran 2005). Exposure: exposure time excluding the detector deadtime; for *XMM-Newton* observations the exposure times are given for the PN, MOS1 and MOS2 detectors, respectively; The data sets without exposure time were not used due to the severe event pile-up. Observation Mode: PSW: prime small window, PFW: prime full window. For the *XMM-Newton* observations the observations modes are given for the PN, MOS1 and MOS2 detectors, respectively. Filter: optical blocking filter selected for the *XMM-Newton* detectors.

^aData from XMM000726 and XMM000728 are combined and denoted as XMM0007.

^bData from XMM030125, XMM030127A, XMM030127B, XMM030129 and XMM030130 are combined and denoted as XMM0301.

^cSpectra from CXO030720 and XMM030722 are simultaneously fit and those results are denoted as CXOXMM0307.

imum, the variation of the absorbing material in front of the X-ray emitting region near the X-ray minimum, the nature of the rapid fall from X-ray maximum to X-ray minimum, the excess in N_H after recovery.

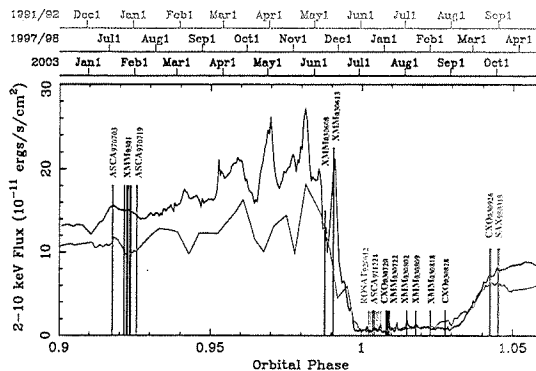
The minimum which occurred in mid-2003 was among the best observed astronomical events of all time. A key part of this campaign were the detailed X-ray observations obtained with *RXTE*, *Chandra*, and *XMM-Newton*. *RXTE* again provided crucial monitoring of the daily changes in X-ray flux, while *Chandra* provided previously-unobtainable monitoring of the X-ray emission line dynamics at key phases of the binary period. *XMM-Newton* obtained critical measurements of the spectrum of the source during the low-flux state when observations with *RXTE* or *Chandra* are difficult.

This paper describes the overall change of the X-ray spectrum of η Car around the 2003 minimum as measured by *XMM-Newton* (Jansen et al. 2001), supplemented where necessary with key observations with *Chandra* (Weisskopf et al. 2002). We try to understand the X-ray emission and absorption mechanism and the cause of the X-ray minimum, from a comparison of derived spectral properties such as kT , N_H and emission line strengths in these observations and earlier *ROSAT* and *ASCA* observations during the 1992 and 1997/98 minima.

The paper is comprised of the following sections. Section 2 describes the observations and method of the data reduction, and includes a description of problems of unresolved emission components around the central source in the extracted *XMM-Newton* source events. Section 3 describes imaging and timing analyses of the *XMM-Newton* data. Section 4 describes the analysis of the X-ray spectra during the 2003 minimum. Section 5 compares the X-ray spectra during the 2003 minimum to the previous minima in 1998 and 1992. We discuss our results in section 6, and in section 7 we summarize our conclusions.

2. Observations & Data Reduction

In 2003, *XMM-Newton* observed η Car a total of 11 times, 5 times in January 2003 (about 6 months before the onset of the 2003 minimum), twice in June 2003 (weeks before the onset of the 2003 min-



mode outside the 2003 minimum when the star was bright in the 2–10 keV band. We did not use these data sets in our analysis. *XMM-Newton* is also equipped with the Reflection Grating Spectrometer (RGS; den Herder et al. 2001), but the RGS has limited sensitivity above ~ 1 keV, where emission from the WWC region dominates. We therefore did not use the RGS data.

The analysis of the *XMM-Newton* data was performed with version 5.4.1 of the SAS¹ software package and version 5.2 of the HEASoft² analysis package. The Observation Data Files (ODF) data were processed using the SAS scripts “emchain” and “epchain.” We removed events close to hot pixels or outside the field of view, and selected events with pattern ≤ 4 for EPIC PN spectral analysis and pattern ≤ 12 for timing analysis of the EPIC PN data and spectral and timing analysis of the EPIC MOS data. Most of these observations luckily avoided high background periods and the instrumental background is negligible in any observations within the 0.3–10 keV band. We did not need to reject any high background periods because the strong emission from η Car greatly surpassed the observed background levels.

Due to the limited spatial resolution of *XMM-Newton*, the extracted η Car data inevitably include emission from a number of sources (see Figure 2). The extracted spectrum is usually dominated by hard X-rays from the wind-wind collision in η Car, which varies from observation to observation (Corcoran et al. 2000; Viotti et al. 2002). The Homunculus Nebula emits weak diffuse reflected X-rays from the central source, which can be spatially resolved only with *Chandra* and only during the minimum (Corcoran et al. 2004). The outer ejecta extending about $1'$ beyond the Homunculus Nebula emits diffuse non-variable X-rays below ~ 1 keV with a ring- or shell-like morphology (Seward et al. 2001; Weis et al. 2004). To correct the *XMM-Newton* spectra for emission from the outer ejecta and the Homunculus Nebula, we used three *Chandra* data sets from the 2003 X-ray observing campaign, two observations during the 2003 minimum and an observation just after the 2003 minimum. These *Chandra* observations spatially resolve the outer ejecta emission from the emission

of the stellar source and so allow us to determine the spectrum of the outer emission, which we can then use to help model the *XMM-Newton* spectra.

The log of *Chandra* observations and the timing of the observations are also given in Table 1 and Figure 1. *Chandra* observations are designated CXO, subscripted with the year, month and day of the observation, similar to our designation of the *XMM-Newton* observations. The *Chandra* observations were obtained using the Advanced CCD Imaging Spectrometer detector using the Spectrometer array (ACIS-S) either with or without the high energy transmission grating (HETG). For the grating data, 0th-order photon events were used for CXO₀₃₀₇₂₀ (during the X-ray minimum, when the source was too faint at 1st order), and 1st-order photon events were used for CXO₀₃₀₉₂₆ after the recovery since the central source had severe pile-up in the 0th-order data. The observation CXO₀₃₀₈₂₈, taken during the minimum with the ACIS-S imaging array with no grating, also suffered mild pile-up ($\sim 4\%$). The analysis of the *Chandra* data was performed with the CIAO³ software package, version 2.3 (CALDB version 2.22), version 3.0 (CALDB version 2.23) and version 3.0.2 (CALDB version 2.26) for sequences 200216, 200237, and 200217 respectively. We also used version 5.2 of the HEASoft package, and followed the recommendations of the analysis science thread⁴. A full analysis of the *Chandra* spectra will be published separately (Corcoran et al. 2007, in preparation).

3. X-ray Images and Time Variability

All *XMM-Newton* images similarly showed emission from the central source and the outer ejecta (Figure 2). Because these *XMM-Newton* images cannot completely separate emission from the outer ejecta and central source nor resolve the faint X-ray Homunculus Nebula (Corcoran et al. 2004), we used an ellipse of $50'' \times 37.''5$ as the source region (called “XMM SRC” in Figure 2), which includes all these emission components but excludes nearby X-ray luminous stars (such as HDE 303308) more than $\sim 1'$ distant. For some small window mode MOS observations, the south-east tip of the ellipse fell outside the small

¹http://xmm.vilspa.esa.es/external/xmm_sw_cal/sas_frame.shtml

²<http://heasarc.gsfc.nasa.gov/docs/software/lheasoft/>

³<http://cxc.harvard.edu/ciao/>

⁴<http://cxc.harvard.edu/ciao/threads>

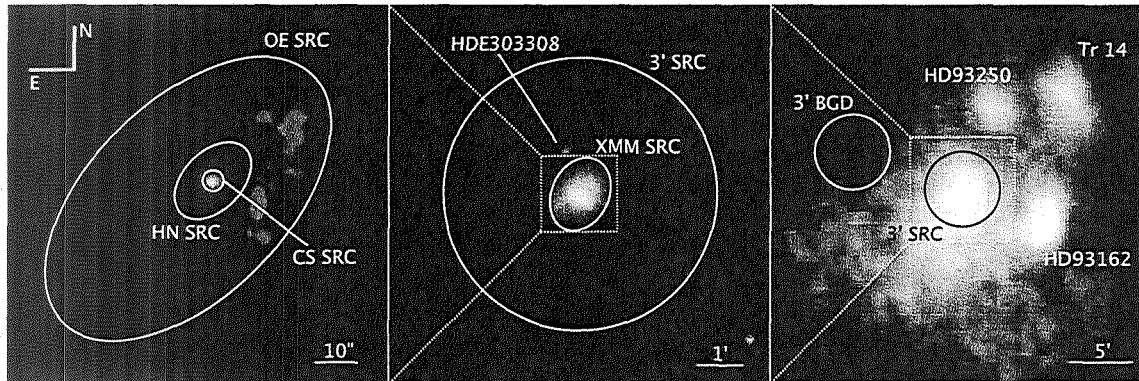


Fig. 2.— True color images of η Car. *left*: *Chandra* HETG 0th-order data from CXO₀₃₀₇₂₀ (red: 0.2–1 keV, green: 1–3 keV, blue: 3–10 keV); *middle*: *XMM-Newton* image accumulated from all the available MOS data taken in prime full window mode (red: 0.2–1 keV, green: 1–3 keV, blue: 3–9 keV); *right*: *ASCA* GIS data from ASCA₉₇₁₂₂₄ (red: 0.8–1 keV, green: 1–3 keV, blue: 3–10 keV). The color in the *ASCA* image has been chosen to highlight the diffuse emission. Solid lines show source (SRC) or background (BGD) regions (Designations: OE: Outer Ejecta, HN: Homunculus Nebula, CS: Central Source). The *Chandra* and *ASCA* images were smoothed with a Gaussian with $\sigma = 1.5$ pixel, while the *XMM-Newton* image was not smoothed.

window. We determined background using regions from apparently source-free regions on the same CCD chip.

Table 2 shows detected photon count rates in the soft (0.3–1 keV), medium (1–4 keV), and hard (4–10 keV) bands in each detector for each observation. The soft band mainly includes emission from the outer ejecta, while the medium band includes emission from an additional source which we call the central constant emission component (CCE, see §4.1.2), and the medium band outside the minimum and the hard band includes the WWC emission (see §4.2). In the soft band, the MOS2 count rates are 10% lower in XMM₀₀₀₇ than during the 2003 minimum because of the use of a smaller MOS2 source region for the XMM₀₀₀₇ data. The soft-band PN count rates are slightly higher outside minimum because the spectral response of the PN allows photons from the bright hard source to contaminate the soft band. For example, we estimate the soft band contamination due to the hard photons in XMM₀₀₀₇ to be ~ 0.08 counts s^{-1} , which makes the corrected PN count rates in the soft band 1.06 counts s^{-1} in this observation. This means that the emission from the outer ejecta was constant to $\lesssim 2\%$ to better than 90% confidence over a half-year interval. On

the other hand, both the medium and hard band count rates decreased dramatically to ~ 1 –5% of the maximum brightness seen by *XMM-Newton*.

We constructed light curves with 500 s time bins, combining all the available MOS and PN data. In Figure 3, we show three sample light curves, representing variations before the minimum (XMM₀₃₀₆₁₃) and during the minimum (XMM₀₃₀₇₂₂, XMM₀₃₀₈₁₈). In general, these light curves showed no significant variation in most energy bands at $>90\%$ confidence (Table 2, Figure 3). The exceptions are the medium band light curves before the 2003 minimum. The medium band light curve from the XMM₀₃₀₆₀₈ observation showed an “excess” of ~ 0.2 counts s^{-1} ($\sim 4\%$) near the middle of the observation, while the medium band light curve from the XMM₀₃₀₆₁₃ observation showed a slight linear increase by $\sim 0.54^{+0.21}_{-0.22}$ counts s^{-1} day $^{-1}$ ($1\text{-}\sigma$) or $\sim 10\%$ day $^{-1}$. The linear model is still not accepted above the 90% confidence level ($\chi^2/\text{d.o.f.} = 1.59$), due to small fluctuation on timescales of $\lesssim 500$ s. We note that the hard band light curve in XMM₀₃₀₆₁₃ is also better reproduced by a linearly-increasing model with a slope of $\sim 0.78^{+0.32}_{-0.26}$ counts s^{-1} day $^{-1}$, or $\sim 7.5\%$ day $^{-1}$, with $\chi^2/\text{d.o.f.} = 0.98$. This increase is roughly consistent with

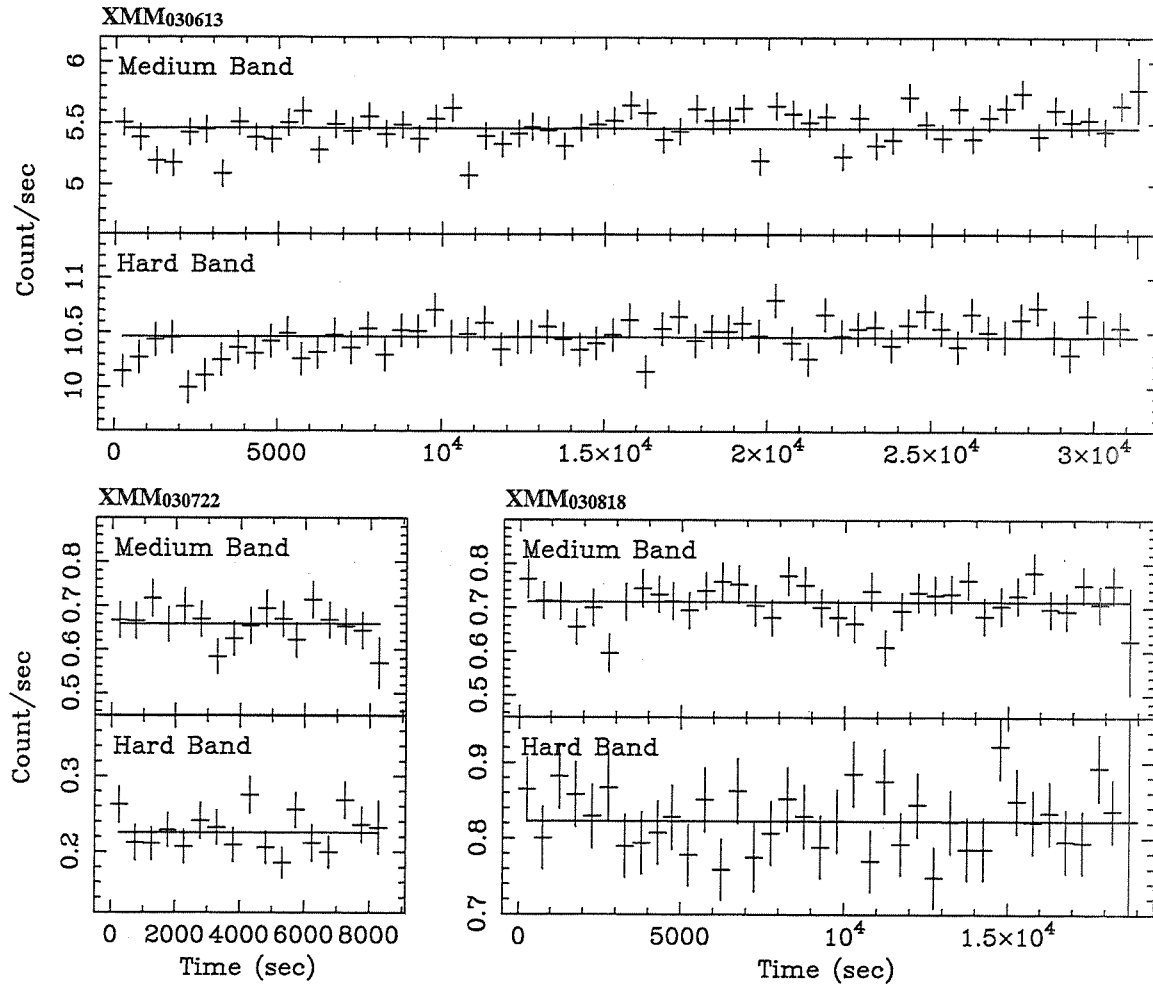


Fig. 3.— Background subtracted EPIC PN + MOS light curves from XMM₀₃₀₆₁₃ (*top*), XMM₀₃₀₇₂₂ (*bottom left*), and XMM₀₃₀₈₁₈ (*bottom right*). Top and bottom graphs in each panel show the medium (1–4 keV) and hard (4–10 keV) bands, respectively. A solid line in each panel shows the best-fit constant model.

TABLE 2
TIME VARIABILITY

Observation	Net Count Rate									Constant Model Fit			
	Soft[0.3–1 keV]			Med[1–4 keV]			Hard[4–10 keV]			$\chi^2/\text{d.o.f.}$			
	PN	MOS1	MOS2	PN	MOS1	MOS2	PN	MOS1	MOS2	Soft	Med	Hard	d.o.f
	(counts s ^{−1})			(counts s ^{−1})			(counts s ^{−1})						
XMM0007	...	...	0.255 ^a	...	...	1.25 ^a	...	...	0.91 ^a	0.97	1.12	0.82	76
XMM0301	1.15	...	...	7.72	...	...	7.18	...	...	0.98	1.14	1.05	75
XMM030608	1.10	0.247 ^a	...	4.58	1.70 ^a	...	6.77	1.89 ^a	...	0.99	1.45	0.95	55
XMM030613	1.09	0.242 ^a	...	4.99	1.84 ^a	...	10.49	2.80 ^a	...	1.02	1.84	1.29	62
XMM030722	1.03	0.223 ^a	0.285	0.456	0.170 ^a	0.188	0.183	0.045 ^a	0.049	0.81	0.85	1.31	16
XMM030802	1.07	0.222 ^a	0.288	0.464	0.161 ^a	0.190	0.517	0.137 ^a	0.124	0.97	1.21	0.75	34
XMM030809	1.06	0.226 ^a	0.280	0.476	0.178 ^a	0.188	0.554	0.159 ^a	0.151	1.13	0.79	1.09	24
XMM030818	1.05	0.221 ^a	0.288	0.514	0.169 ^a	0.202	0.648	0.179 ^a	0.174	1.34	0.96	0.92	37

^aSource regions are slightly smaller for these Prime Small Window observations.

the *RXTE* light curve ($\sim 15\%$ day⁻¹, see Figure 1).

4. X-ray Spectra

For each *XMM-Newton* observation, we produced EPIC PN and MOS spectra using the same source and background regions as in §3. Figure 4 presents the EPIC PN spectra for all 2003 observations. The X-ray spectra are a combination of a variable hard WWC component, along with non-variable emission from a number of components. Consistent with Table 2, the spectra below 1 keV are almost constant through the observations. Above 1 keV the spectra varied by a factor of 2–3 before the 2003 minimum, then decreased dramatically by more than an order of magnitude after the onset of the 2003 minimum in June, with small recovery by a factor of ~ 3 at $E \gtrsim 4$ keV during August. Most spectra clearly showed lines of hydrogen- and helium- like ions of Mg, Si, S, Ar, Ca, Fe, and Ni, and a fluorescence line from cold Fe.

In the following we examine first the non-variable emission, then use this emission to fully understand changes in the variable component. In our analysis, we adopt abundances relative to solar abundances given by Anders & Grevesse (1989)

4.1. Non-Variable Components

4.1.1. Contribution of the Outer Ejecta and Homunculus Nebula to the X-ray Spectra

We use *Chandra* observations to estimate the amount of contamination from the outer ejecta

and the Homunculus Nebula in the *XMM-Newton* spectra.

We extracted the spectrum of the outer ejecta from the *Chandra* CXO030720 HETG 0th-order data, which has the smallest contamination from the central hard source. We extracted the source spectrum from an $83'' \times 47''$ ellipse centered on the star (“OE SRC” in Figure 2), with its major axis parallel to the long axis of the extended outer X-ray nebula, but excluded a $20'' \times 15''$ ellipse (“HN SRC” in Figure 2) centered on the central source and the Homunculus Nebula. We extracted background spectra from a nearby apparently source-free region. η Car is embedded in soft diffuse emission from the Carina nebula, but its contribution to the η Car spectrum is negligible.

The spectrum from the “OE SRC” region, excluding the spectrum from the “HN SRC” region, is shown in Figure 5. This spectrum shows a strong emission line from nitrogen, which reconfirms the N enhancement in the outer ejecta found by a number of previous analyses, (optical/UV: Davidson et al. 1982, X-rays: Tsuboi et al. 1997 [N/O ~ 5], Leutenegger et al. 2003 [N/O > 9]). This spectrum also shows a significant excess at 1.3 keV, the energy of the helium-like Mg line, which seems to require a Mg overabundance of $\gtrsim 3$ solar at $kT \sim 0.6$ keV (though plasma with that temperature should emit a stronger hydrogen-like Mg line). Leutenegger et al. (2003) also found a similarly strong Mg line in the *XMM-Newton* grating spectrum, though they conjectured that some of the Mg emission might be contamination from the stellar X-ray source. Our re-

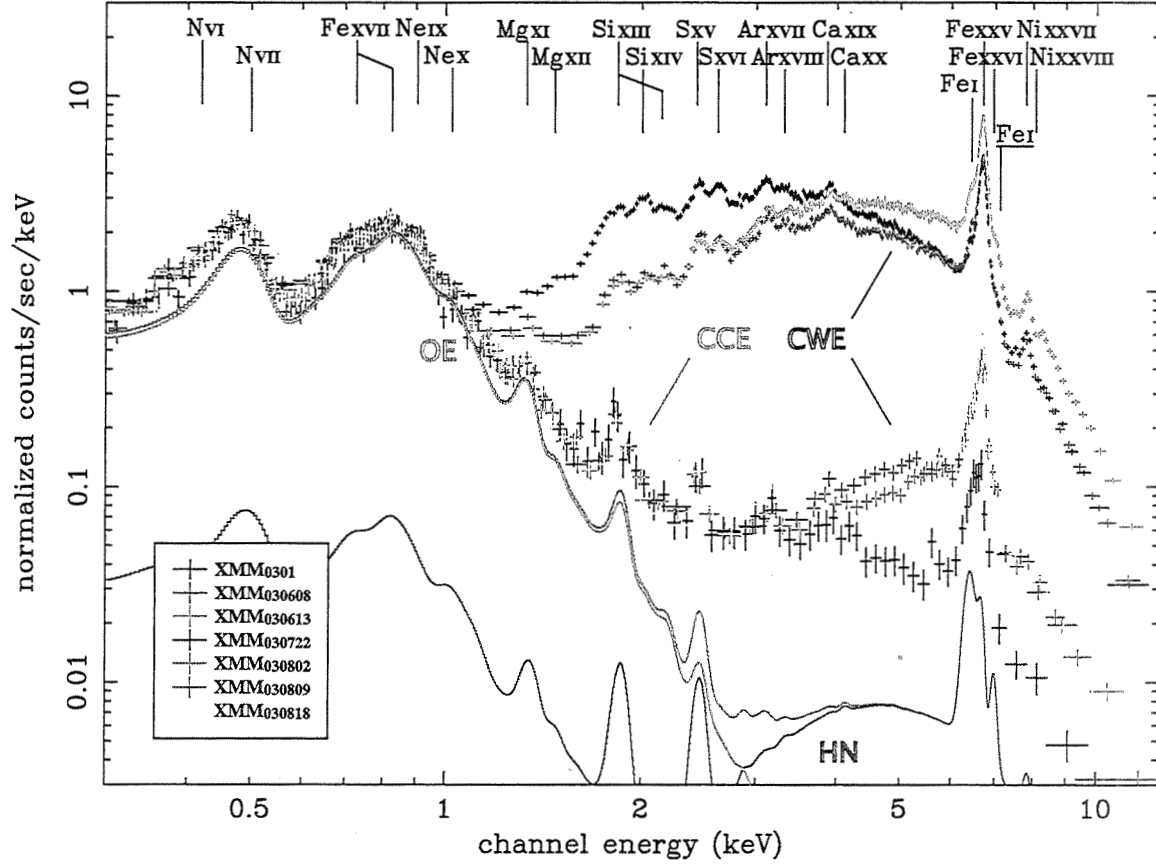


Fig. 4.— *XMM-Newton* EPIC PN spectra of η Car in 2003. The central source [central constant emission (CCE) and colliding wind emission (CWE)] component, the Homunculus Nebula (HN) and the outer ejecta components (OE) are marked. Identified emission lines are marked by lines at their rest energies. Fe I marks the location of the Fe absorption edge. The red, blue, and grey lines show *Chandra* best-fit models of the outer ejecta (see Figure 5), the Homunculus Nebula, and their sum, folded through the EPIC PN effective area.

sults suggest that the Mg line does in fact originate in the outer nebulosity. We modeled the extracted, background-corrected source spectrum below 3 keV (where the emission from the extended source dominates) using a simple absorbed optically thin, thermal plasma model (WABS, Morrison & McCammon 1983; MEKAL, Mewe et al. 1995), including the ACISABS⁵ component to compensate for the progressive low energy degradation of the quantum efficiency of the *Chandra* ACIS detector. We allowed the abundances to vary, but constrained all abundances to have the same value except for nitrogen, which was allowed to vary independently. We added a Gaussian with a fixed line centroid at 1.31 keV with no intrinsic broadening, to account for the helium-like Mg line emission. The model successfully reproduces the spectrum of the outer ejecta, yielding a reduced χ^2 of 1.09 for 81 dof, with the best-fit parameters of $kT \sim 0.58$ keV, $N_H \sim 7.2 \times 10^{20} \text{ cm}^{-2}$, with a VMEKAL normalization of 7.2×10^{-4} , elemental abundance of ~ 85 solar for nitrogen, near solar abundance for the others, and an excess flux of $\sim 1.5 \times 10^{-5} \text{ counts cm}^{-2} \text{ s}^{-1}$ for Mg. The plasma temperature, ~ 0.6 keV – mainly constrained by continuum above 1 keV – agrees well with the highest plasma temperature derived from the emission lines in the *XMM-Newton* grating spectrum (Leutenegger et al. 2003). However, the N_H is smaller than interstellar absorption to η Car ($\gtrsim 3 \times 10^{21} \text{ cm}^{-2}$, see §2.2 of Leutenegger et al. 2003), the nitrogen abundance is overestimated from earlier measurements, and the best-fit model does not reproduce the Fe L and Ne lines near 1 keV that are observed with the high resolution grating spectrum. This is perhaps caused by assuming a simplistic 1T model for a spectrum which may have multiple cooler plasma components. Therefore, this model reproduces CCD-resolution spectra ($\gtrsim 100$ eV at 1 keV) at energies above ~ 0.4 keV but not higher-resolution grating spectra.

The reflected X-ray emission from the Homunculus Nebula did not vary significantly between CXO₀₃₀₇₂₀ and CXO₀₃₀₈₂₈, an interval of 40 days (Corcoran et al. 2004). Since this emission represents the accumulated X-rays reflected from

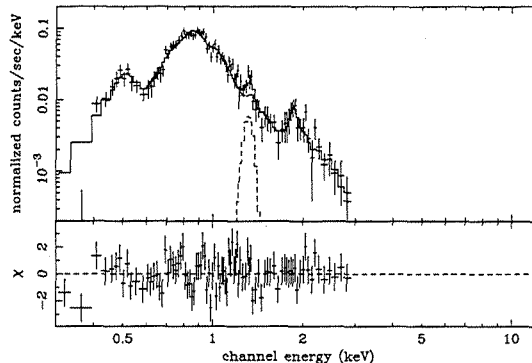


Fig. 5.— *Chandra* spectrum of the outer ejecta from CXO₀₃₀₇₂₀ (OE SRC – HN SRC in Figure 2). The solid line shows the best-fit absorbed 1T model and the dashed line depicts the Gaussian component for helium-like Mg.

the entire Homunculus Nebula, any time variation of the central source shorter than the average light-travel time from the star to the reflecting site inside the Homunculus Nebula (~ 88 days) will be smeared out. We assume that the emission from the Homunculus Nebula did not vary between CXO₀₃₀₇₂₀ and CXO₀₃₀₈₂₈, which includes all *XMM-Newton* observations during the 2003 minimum (XMM₀₃₀₇₂₂ – XMM₀₃₀₈₁₈). To show the relative magnitude of the contamination from this reflected component, in Figure 4 we include a model fit of the *Chandra* spectrum of the reflected X-rays from the Homunculus Nebula, which we extracted from a $20'' \times 15''$ ellipse centered on the star (HN SRC in Figure 2), excluding a $2.''5$ radius circle (CS SRC).

Though the X-ray intensity of the Homunculus in observations outside the 2003 minimum is less certain, at these times the X-ray emission from the central source was so bright that the X-ray contamination from the Homunculus is $\lesssim 1\%$ even if the reflected emission from the Homunculus brightened by a factor of ~ 3 .

4.1.2. Discovery of a “Constant” Component Near the Central Source

Figure 4 depicts the *XMM-Newton* EPIC PN spectra recorded through 2003, along with the best-fit spectral models of the outer ejecta, the X-ray Homunculus Nebula, and their sum. Ex-

⁵<http://cxc.harvard.edu/cont-software/ACISABS.1.1.html>

TABLE 3
BEST FIT PARAMETERS OF THE CCE COMPONENT

Parameters	1T fit
kT (keV)	1.05 (0.96–1.13)
$Z(\text{Si})$ (solar)	0.22 (0.14–0.29)
$Z(\text{S})$ (solar)	0.47 (0.39–0.55)
$E.M.$ (10^{56}cm^{-3})	7.0 (6.0–8.2)
N_{H} (10^{22}cm^{-2})	4.96 (4.77–5.16)
L_{X}^{a} ($10^{34}\text{ergs s}^{-1}$)	1.3
$\chi^2/\text{d.o.f}$	1.51
d.o.f	1205

NOTE.—Elemental abundances of the hard component were found to be non-solar, but do not vary with observation.

^aAbsorption corrected X-ray luminosity between 0.5–10 keV, assuming the distance of 2.3 kpc.

cept for the excess below 1 keV, which is produced by the poor absolute flux calibration of the EPIC PN⁶, the excess over the summed spectrum represents emission in a region (CS SRC in Figure 2) within 2."5 of the hard X-ray peak. Apparent in Figure 4 is an excess over the model in the energy range 1 – 3 keV. This emission apparently did not vary in time with the harder emission, and had the same flux in the *Chandra* spectra of the central region in observations CXO₀₃₀₇₂₀, CXO₀₃₀₈₂₈, and CXO₀₃₀₉₂₆ (see also Figure 6), so that the emission was securely constant for more than two months between July 20 – September 26 2003. We call this component the Central Constant Emission component, or "CCE".

The CCE shows lines of helium-like S and Si ions but no lines of hydrogen-like S and Si ions. This indicates that the CCE comes from relatively cool plasma. To estimate the emission parameters of the CCE, we subtracted contributions of the outer ejecta and Homunculus Nebula from both the PN and MOS spectra (see the top panel of Figure 6 which shows the PN spectra). We ignored data bins below 1.4 keV, where the MOS and PN spectra have significant discrepancies due to problems with the relative flux calibrations between the two instruments. To better estimate the spectrum at low energies, we also fit the *Chandra* spectra of the central region from CXO₀₃₀₇₂₀ and CXO₀₃₀₈₂₈ (see the bottom panel of Figure 6).

⁶see the *XMM-Newton* calibration report CAL-TN-0018-2-3

Because of the finer spatial resolution of *Chandra*, these spectra are mostly free from contamination by emission from the outer ejecta. Each *XMM-Newton* and *Chandra* spectrum was fit by a combination of a low and high temperature, optically thin thermal plasma model with independent absorbing columns for each component, including a Gaussian line to account for the fluorescence iron line at 6.4 keV. The low temperature component accounts for the emission from the CCE.

The parameters of the low temperature component were tied among all the spectra, and we assumed fixed solar abundances for all elements except for silicon and sulfur, whose abundances were allowed to vary simultaneously for all the spectra. We allowed the parameters of the hard component (which represents the variable emission of the stellar source) to vary among all the spectra, but we kept the abundances at the same (non-solar) values in each spectrum. Table 3 shows the best-fit parameters for the constant component. The spectrum can be fit with $kT \sim 1.1$ keV, $N_{\text{H}} \sim 5.0 \times 10^{22} \text{cm}^{-2}$, with an absorption corrected luminosity of $\log L_{\text{X}} \sim 34 \text{ergs s}^{-1}$, and low abundances for Si (~ 0.21 solar) and S (~ 0.47 solar).

The model, however, was not accepted at above 90% confidence for the following reasons: i) The *Chandra* spectra show significant excess below ~ 1 keV, perhaps originating in foreground emission from the outer ejecta "bridge" (Weis et al. 2004, see also Figure 2). The excess can be reproduced by including some flux from the outer

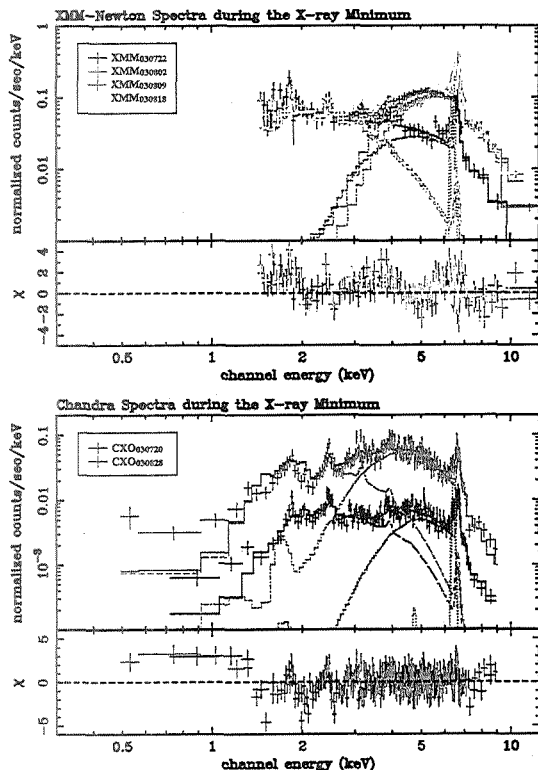


Fig. 6.— *Top:* *XMM-Newton* EPIC PN spectra during the 2003 minimum (XMM030722–XMM030818) after subtracting emission from the outer ejecta and Homunculus Nebula. *Bottom:* *Chandra* spectra of the central region in CXO030720 (black, HETG 0th-order) and CXO030828 (red, ACIS-S). The solid lines show the best-fit model of a simultaneous fitting of *XMM-Newton* (PN and MOS) and *Chandra* spectra by an individually absorbed 2T model. Barred, dot-bar, and dotted lines show the CCE component, variable component, and a Gaussian for the Fe K fluorescence line, respectively.

ejecta using the model derived in §4.1.1. This slightly improves the reduced χ^2 from 1.51 for 1205 to 1.50 for 1203 degrees of freedom. The included flux is $\sim 0.4\%$ of the whole outer ejecta emission. ii) The model overestimates the spectra near 2 and 2.7 keV, where lines of hydrogen-like Si and S ions are, and the model underestimates the spectra near 1.8 and 2.5 keV, where lines of helium-like Si and S ions are. This suggests that the constant component includes plasma with temperature cooler than $kT \sim 1$ keV, though an inconsistency near 2 keV between *XMM-Newton* and *Chandra* spectra could also be caused by calibration uncertainties of the *Chandra* effective area around the iridium M-edge. Since cooler plasmas have lower emissivities in those lines, our simple 1T model fitting for the CCE component can underestimate the elemental Si and S abundances. iii) The model underestimates the *XMM-Newton* spectra near 3–4 keV, possibly because the variable component is a multiple temperature plasma (see §4.2.2). iv) The Fe K line profile is complex and cannot be fit by a simple 1-temperature equilibrium model (see §4.2.3). Nevertheless, the parameters given in Table 3 should approximate the physical properties of the CCE, except perhaps for the elemental abundances, which are more dependent on details of the model.

As seen in Figure 6, the emission between 1–3 keV in CXO030720 comes predominantly from the CCE component. The 1–3 keV image in CXO030720 was apparently point-like, which restricts the projected plasma size to within $\sim 1''$ of η Car, the width of the *Chandra* point-spread function. This is equivalent to a projected distance $\lesssim 2300$ AU at $d \sim 2.3$ kpc, suggesting that the hot gas which produces the CCE component is inside the Little Homunculus Nebula (which has a projected extent of $\sim \pm 2''$, Ishibashi et al. 2003).

4.2. The Variable Component

In order to determine the spectrum of the variable stellar component, we then subtracted from all the original spectra the recognized non-variable emission components – the outer ejecta, the X-ray Homunculus Nebula, and the CCE component. The remaining emission represents the variable component associated with the stellar source, and is shown in Figure 7. The top panel shows the variable component “corrected” for the con-

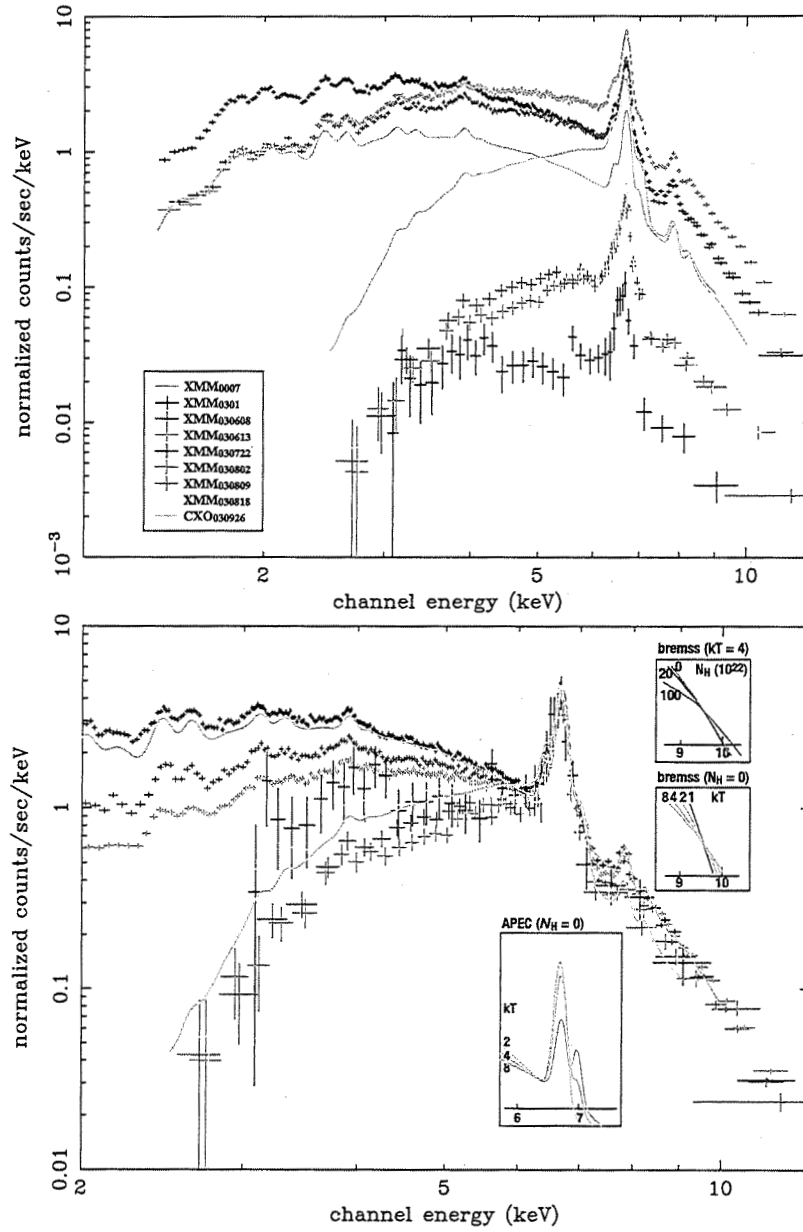


Fig. 7.— *Top*: XMM-Newton spectra of the variable emission. *Bottom*: XMM-Newton spectra renormalized to the line intensity of the helium-like Fe line. Best-fit models of the variable emission in XMM0007 and CXO030926, convolved with the EPIC PN effective area, are also displayed in grey and orange. Each color represents the same observation as in Figure 4. Boxes in the bottom panel show the high energy slopes of the bremsstrahlung emission at $kT = 4$ keV with $N_H = 0, 2$, and $10 \times 10^{23} \text{cm}^{-2}$ (*top*), the bremsstrahlung emission at $kT = 1, 2, 4$, and 8 keV without absorption (*middle*), and Fe line profile of the APEC model at $kT = 2, 4$, and 8 keV with abundance of 0.5 solar (*bottom*).

stant components we identified. For comparison, we overlaid on the top panel of Figure 7 the best-fit models for the XMM0007 and CXO030926 datasets.

4.2.1. Variation of the Overall Spectral Shape

The bottom panel of Figure 7 shows the “corrected” variable components normalized at the Fe XXV line energy to highlight changes in the shape of the spectra. From XMM0007 to XMM0301 (an interval of 2.5 years) the X-ray flux increased by a factor of 2–3 without remarkable changes in spectral shape. Four months later (observation XMM030608), the X-ray emission decreased only below 5 keV. Five days later (observation XMM030613), when η Car was close to the peak of the last flare before the 2003 minimum (Corcoran 2005), the hard X-rays above ~ 3 keV increased by a factor of two. The X-ray emission dropped by almost two orders of magnitude by XMM030722, the first observation after the 2003 minimum. In XMM030802, the hard band flux recovered by a factor of 3 without any significant change in the soft band. The hard band flux stayed the same in XMM030802, XMM030809, XMM030818, and CXO030828 (not shown), while the soft band emission slightly increased. The *RXTE* light curves (Corcoran 2005) also show a clear transition in the flux level and hardness ratio between XMM030722 and XMM030802. This means that the X-ray minimum has two states. By CXO030926, only the hard band flux recovered to the pre-minimum level.

The bottom panel in Figure 7 clearly shows that, throughout the observations, the hard band slope above 7 keV did not change significantly, nor did the ratio of hydrogen-like to helium-like Fe ion lines. This means that the electron temperature of the hottest plasma did not change during the 2003 minimum. On the other hand, the soft band flux relative to the hard band decreased gradually from the X-ray maximum through the minimum to the recovery. This looks like an increase of the absorption column to the X-ray plasma though the situation is somewhat more complicated, as the following sections describe. The 2003 minimum can be better described as an apparent decrease of the emission measure (*E.M.*) as suggested by earlier *ASCA* observations (Corcoran et al. 2000), which means that either the amount of X-ray emitting material has declined, or that the amount that is

visible to the observer is smaller.

4.2.2. 1-Temperature Fit of the Entire Spectrum

To quantitatively describe the spectral shapes and compare them with earlier results obtained by *ASCA* and *BeppoSAX* (see §5), we fit each spectrum by an absorbed 1T thermal APEC⁷ model (which provided a better fit near the Fe K lines than the MEKAL model), with a Gaussian at 6.4 keV to account for the Fe K fluorescence line. The results are listed in Table 4.

Most of the fits were not acceptable at the 90% confidence level. One reason for the poor fit by the absorbed 1T models is that the strong Fe K α profile is quite complicated, as described in §4.2.3. Another reason, in particular for the spectra before the 2003 minimum, is that the plasma is really composed of multiple components with different temperatures as shown by Corcoran et al. (2001b), as their best-fit plasma temperatures $kT \sim 4\text{--}5$ keV do not account for the strong lines of helium-like S and Si ions seen in the *XMM-Newton* spectra (which should be emitted from plasma with $kT \sim 1$ keV). The plasma temperatures outside the 2003 minimum ($kT \sim 4\text{--}5$ keV) are consistent with earlier results (Tsuboi et al. 1997; Corcoran et al. 2000; Viotti et al. 2002; Leutenegger et al. 2003), but they are probably overestimated by our 1T model fit (see the next section). The derived absorption column, which does not depend strongly on temperature for $kT \sim 3\text{--}5$ keV, gradually increased from $N_H \approx 5 \times 10^{22} \text{ cm}^{-2}$ to $N_H \approx 4 \times 10^{23} \text{ cm}^{-2}$.

4.2.3. Fits to the $E > 5$ keV Spectrum

The EPIC spectra marginally resolved emission lines below ~ 5 keV and could not reliably measure the neighboring continuum level. Spectral modelling of this energy band with unconstrained elemental abundances, therefore, has intrinsic uncertainty. On the other hand, the spectrum above 5 keV is relatively simple and provides an unambiguous measure of the hottest plasma from the continuum slope and Fe K line intensities. To characterize the hottest plasma, we thus fit the spectra above 5 keV by a simple absorbed 1T model.

⁷<http://cxc.harvard.edu/atomdb/>

TABLE 4
THE BEST-FIT MODELS FOR THE WHOLE SPECTRA

Observation	ϕ_{orbit}	kT (keV)	Z (solar)	Flux _{6.4 keV} (10^{-4} counts $\text{cm}^{-2} \text{s}^{-1}$)	N_H (10^{22} cm^{-2})	Observed Flux ($10^{-11} \text{ ergs cm}^{-2} \text{s}^{-1}$)	reduced χ^2 (d.o.f.)
XMM0007	0.470-0.471	4.6 (4.5-4.8)	0.67 (0.63-0.70)	0.91 (0.75-1.04)	5.1 (5.0-5.2)	6.5	2.85 (315)
XMM0301	0.922-0.924	4.3 (4.2-4.4)	0.64 (0.62-0.65)	2.4 (2.3-2.6)	4.8 (4.7-4.9)	15.0	10.29 (249)
XMM030608	0.988	4.5 (4.4-4.6)	0.83 (0.81-0.85)	4.1 (3.9-4.2)	7.4 (7.3-7.5)	12.8	12.77 (417)
XMM030613	0.990	5.4 (5.4-5.5)	0.95 (0.94-0.97)	6.9 (6.7-7.1)	9.1 (9.0-9.2)	19.3	17.49 (548)
CXOXMM0307	1.008-1.009	3.1 (2.8-3.6)	0.44 (0.37-0.53)	0.16 (0.13-0.20)	28 (25-32)	0.19	1.24 (193)
XMM030802	1.015	3.6 (3.3-3.9)	0.64 (0.56-0.71)	0.65 (0.58-0.78) ^b	42 (39-45)	0.75	2.44 (119)
XMM030809	1.018	2.9 (2.8-3.1)	0.64 (0.58-0.71)	0.55 (0.45-0.65) ^b	36 (34-38)	0.82	1.19 (94)
XMM030818	1.023	2.9 (2.8-3.1)	0.58 (0.54-0.63)	0.37 (0.26-0.42) ^b	29 (27-30)	0.96	1.30 (161)
CXO030828 ^a	1.028	4.6 (3.4-5.4)	0.48 (0.37-0.60)	0.31 (0.3-0.43)	18 (17-21)	0.73	1.54 (137)
CXO030926	1.042	2.9 (2.3-3.3)	0.40 (0.36-0.45)	3.6 (3.0-4.3)	36 (33-40)	6.6	1.40 (242)

NOTE.—These fits refer to the spectrum between 2–10 keV after subtraction of the CCE and the Homunculus emission. Parentheses show the range of values for which $\Delta\chi^2 = 2.7$ from the best-fit value.

^a About 4% of the photon events are piled-up, causing the spectrum to appear slightly harder.

^b These values are upper-limits since the line shapes are not clearly seen in the spectra.

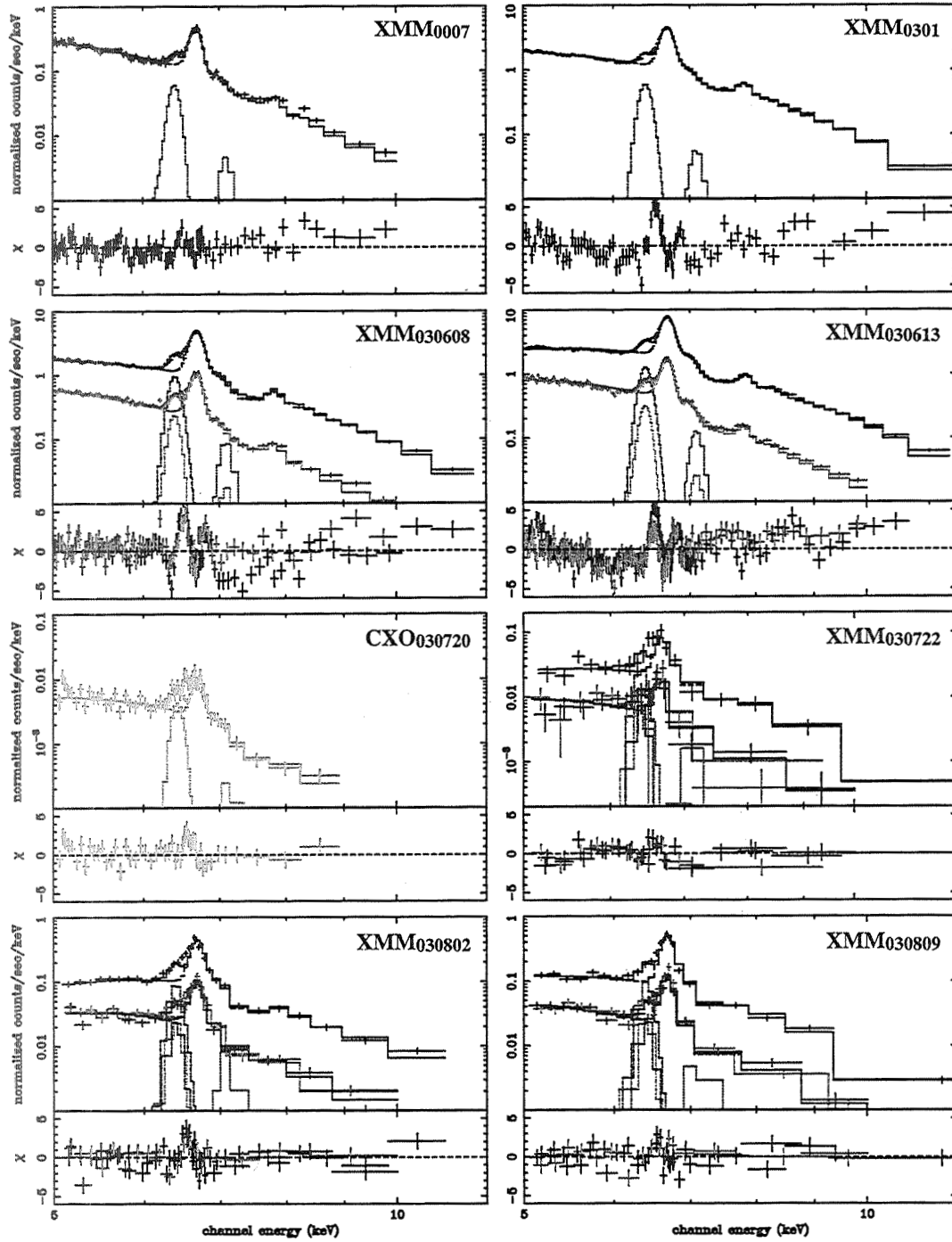


Fig. 8.— Spectra above 5 keV: EPIC PN (black), EPIC MOS1 (red) and MOS2 (blue), ACIS (green) and HETG (grey: +1st order, brown: -1st order). The solid lines show the best-fit absorbed optically thin-thermal plasma model (APEC code) with Gaussian components for Fe K α and β .

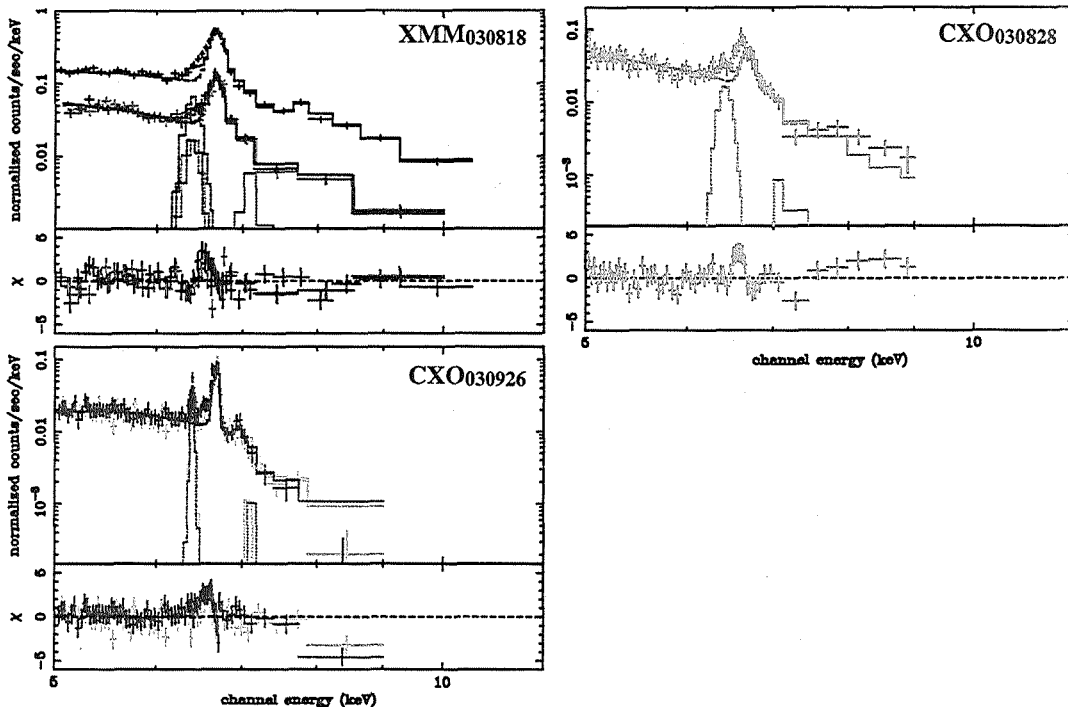


Fig. 8. — Continued.

In each observation, we simultaneously fit all the available spectra, using an APEC thermal equilibrium model for the thermal emission. We simultaneously fit the spectra of two observations, CXO030720 and XMM030722, which were obtained during the 2003 minimum within 2 days of each other. A preliminary fit to the bright phase spectra showed that most spectra could be fit with $kT = 3.3$ keV, a nickel abundance near 0.8 solar, with solar abundances for other elements. Therefore, we fixed the nickel abundance at 0.8 solar and the temperature at 3.3 keV, and we varied the Fe abundance, column density and emission measure. We included 2 narrow Gaussian lines to account for lines of Fe $K\alpha$ and $K\beta$ fluorescence, fixing their centroids at 6.4 keV and 7.1 keV, with their line widths (σ) fixed at 0.01 keV, and the $K\beta$ line flux fixed at 11.3% of the $K\alpha$ line flux. We used photoelectric absorption cross-sections calculated by Balucinska-Church & McCammon (1992). Table 5 gives the best-fit parameters, and the spectra, along with their best-fit models, are shown in Figure 8. The spectra except for XMM0007 and CXOXMM0307 accept the assumed model at

<90% confidence, mostly because these spectra show several spectral features which are not fit by the model.

The most prominent of these features are excesses on the blue and red sides of the K-shell lines of helium-like iron. Those excesses are not caused by poor energy or gain calibration, since there is good consistency in profile between the XMM030613 spectrum and the near-contemporaneous *Chandra* grating spectrum. The blue excess could be explained if the K lines of Fe XXV are Doppler broadened, with $\Delta v \sim 4000$ km s $^{-1}$. This is similar to the derived wind velocity of the companion star, $v \approx 3000$ km s $^{-1}$ (Pittard & Corcoran 2002). The red excess, especially during the 2003 minimum and CXOXMM0307 and XMM030802 when the X-ray flux was the weakest, would require a Fe XXV Doppler shift of $\Delta v \sim 7000$ km s $^{-1}$, and such high velocities are not expected in η Car. However, the red excess may be produced by unresolved emission lines of Fe in ionization stages below Fe XXV in the 6.5–6.6 keV band. Interestingly, the *ASCA* minimum spectrum in ASCA971224 showed a sim-

TABLE 5
THE BEST-FIT MODELS FOR THE SPECTRA ABOVE 5 KEV

Observation	ϕ_{orbit}	Z_{Fe} (solar)	$\log E.M.$ (cm^{-3})	EW(Fe) (eV)	N_H (10^{22} cm^{-2})	reduced χ^2 (d.o.f.)
XMM0007	0.470–0.471	0.48 (0.45–0.52)	58.1 (58.1–58.2)	87 (62–99)	17 (14–20)	1.43 (86)
XMM0301	0.922–0.924	0.48 (0.47–0.50)	58.5 (58.5–58.5)	99 (85–104)	17 (16–19)	4.07 (82)
XMM030608	0.988	0.55 (0.54–0.57)	58.5 (58.5–58.5)	164 (158–172)	21 (20–22)	4.21 (154)
XMM030613	0.990	0.44 (0.43–0.45)	58.9 (58.9–58.9)	119 (114–123)	36 (35–37)	3.66 (245)
CXOXMM0307	1.008–1.009	0.38 (0.30–0.47)	57.0 (56.9–57.0)	~ 233 (183–325) ^a	40 (32–51)	1.35 (90)
XMM030802	1.015	0.50 (0.46–0.55)	57.7 (57.6–57.7)	$\lesssim 213^a$	53 (48–58)	1.91 (71)
XMM030809	1.018	0.70 (0.63–0.77)	57.5 (57.4–57.5)	$\lesssim 257^a$	32 (26–37)	1.59 (54)
XMM030818	1.023	0.62 (0.57–0.67)	57.5 (57.5–57.5)	$\lesssim 150^a$	27 (23–30)	1.65 (84)
CXO030828 ^b	1.028	0.33 (0.24–0.42)	57.5 (57.4–57.6)	~ 149 (96–214) ^a	37 (28–47)	1.81 (54)
CXO030926	1.042	0.33 (0.29–0.37)	58.7 (58.6–58.8)	110 (90–136)	56 (50–62)	1.54 (130)

NOTE.—These fits refer to the spectrum after subtraction of the CCE and the Homunculus emission. The plasma temperature and the Ni abundance were fixed at 3.3 keV and 0.8 solar, respectively.

^aThese values are regarded as upper-limits since the spectra did not clearly show the iron fluorescence line peak.

^bAbout 4% of the photon events pile-up, causing the spectrum slightly hard.

ilar excess (see §5.2), while a *Chandra* grating spectrum near apastron ($\phi \sim 0.53$) showed a similar broad-band excess (Pittard & Corcoran 2002). Presence of lower-ionization iron lines would indicate that the hottest plasma is no longer in collisional ionization equilibrium at 3.3 keV, and that the electron temperature is higher than the ion temperature. Non-equilibrium ionization (NEI) effects have been claimed in the X-ray spectrum of WR 140, another colliding wind system (Pollock et al. 2005).

Similarly, a hump-like spectral feature is perhaps present between 5–6.4 keV and becomes more noticeable during the early phase of the minima. There are no specific emission lines in this energy band, except a weak Ca XIX line at 4.56 keV. A similar feature is sometimes seen in the X-ray spectra of some AGNs (Tanaka et al. 1995), produced by gravitationally red-shifted material very near the central blackhole. However, there is little evidence that η Car houses a black hole because of the lack of short term X-ray variability and relatively low X-ray luminosity.

A second feature is a hard “tail” at $\gtrsim 9$ keV, best seen in the residuals in XMM0007, XMM0301, XMM030608, and XMM030613 (see Figure 8). This feature is probably not an instrumental or background artifact: none of the spectra (except for CXO030828) suffer photon pile-up, and source count rates are much higher than the background.

During the 2003 minimum the tail seems weaker or non-existent, though this may simply be an artifact since the source is weak at these times. The slope above 9 keV in XMM030613 can be fit by a bremsstrahlung model with $kT \sim 10$ keV or power-law model with $\Gamma \sim 2.3$. Viotti et al. (2004) measured a similar photon index for a hard tail extending up to 150 keV, seen in a *BeppoSAX* PDS spectrum in June 2000 ($\phi \sim 0.46$), but the flux between 13–20 keV, $1.4 \times 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1}$, is about three times larger than the extrapolation of the hard tail we measured in XMM030613. The hard excess we see in the *XMM-Newton* data may be from an extremely hot plasma in the colliding wind region, or from non-thermal emission due to 1st-order Fermi acceleration at the wind contact surface, which would produce a population of relativistic electrons that can upscatter UV photons from the stellar photosphere and/or X-ray photons from the wind-wind shock.

We also clearly see an excess at ~ 8.5 keV in the PN spectra in observations XMM0301 and XMM030613. This feature might be due to emission from K shell lines of heavy metals like Cu and Zn. Though the EPIC instrumental background shows emission from those elements (Strüder et al. 2001), inspection of the EPIC background data provided by the XMM project showed that the instrumental background at this energy was negligible in spectra obtained outside the minimum. This feature could indicate an overabundance of

Cu or Zn, or perhaps be a part of the Cu edge at ~ 9 keV (which would also require a large Cu overabundance as well). On the other hand, the feature might be produced by absorption edges from Fe XXV (~ 8.8 keV) and Fe XXVI at ~ 9.3 keV (Lotz 1967).

Finally, the fourth feature is a marginal dip around 7 keV, which is seen in all the PN spectra, but which is not so prominent in the MOS spectra. This dip could be caused by an underestimate of the line intensity of hydrogen-like Fe ions at 6.9 keV (perhaps due to an underestimate of the maximum plasma temperature) or an underestimate of the strength of the Fe edge structure at 7.1 keV, perhaps indicating larger Fe absorption. This dip is especially noticeable in the observation CXO030926, and will be discussed more fully in the analysis of our *Chandra* HETGS observations (Corcoran et al. in preparation).

4.2.4. Adding a Soft Component to Reproduce the Entire Spectrum

Extrapolation of the model spectrum above 5 keV from the XMM0007, XMM0301, XMM030608, XMM030613, CXO030828 and CXO030926 data to lower energies underestimates the observed emission at $E < 5$ keV, indicating the presence of additional cooler emitting material. We thus modeled the emission below 5 keV by fixing the best-fit model spectrum derived in §4.2.3, and adding another 1T component with independent absorption. The results are given in Table 6 and Figure 9.

These fits were not accepted at $>90\%$ confidence except the fit to the CXO030926 spectra. One reason for the poor quality of the fits is that the fixed hard component, which reproduces emission above 5 keV, somewhat overestimates the emission near 5 keV, which might indicate we slightly underestimated the absorption to the hard component. Another reason is that the best-fit models do not reproduce the strengths or locations of many emission lines, in particular S XIV, which is generally emitted by plasma at $kT > 1$ keV. This means that the spectra may require additional components with kT between 1–3 keV. The N_H values we derive from this 2 component modeling are very close to the ones from the 1T fitting in §4.2.2.

5. Comparison with the Previous Observations Near X-ray Minima

The weekly to daily monitoring of η Car with *RXTE* (Corcoran 2005) showed significant cycle-to-cycle variability in flux and X-ray hardness. Since the *RXTE* data are contaminated by instrumental and cosmic background, we compared our *XMM-Newton* and *Chandra* results with earlier spatially-resolved observations from *ASCA* (Tanaka et al. 1994), *BeppoSAX* (Scarsi 1993) and *ROSAT* (Trümper 1984).

Between phase $-0.10 \lesssim \phi_{\text{orbit}} \lesssim 0.10$, there were 4 *ASCA* observations and 1 *BeppoSAX* observation near the 1998 minimum, and 1 *ROSAT* observation during the 1992 minimum. These observations are summarized in Table 7. Because of the extended point responses (FWHM \sim a few arcminutes) of *ASCA* and *BeppoSAX* compared to *XMM-Newton*, source spectra extracted from these observations used relatively large ($\sim 3'$) extraction regions (Corcoran et al. 2000; Viotti et al. 2002). This extraction area is about a factor of ~ 20 larger than the area used in the *XMM-Newton* analysis (XMM SRC), and about a factor of ~ 5000 larger than the area used in the *Chandra* analysis (CS SRC). Because the neighborhood of η Car is crowded with X-ray sources and diffuse emission, the *ASCA* and *BeppoSAX* spectra will suffer greater contamination from neighboring sources.

5.1. Comparison of the 1997/98 and 2003 Spectra Outside the Minimum

Outside the minimum, contamination of the stellar source spectra in the *ASCA* and *BeppoSAX* observations from the surrounding sources, the CCE component, and the reflection from the Homunculus Nebula is $\lesssim 10\%$ above ~ 2.5 keV (see §5.2).

Viotti et al. (2002) tried two models to fit their *BeppoSAX* spectra: an absorbed single temperature bremsstrahlung model + Gaussian for the spectrum between 3–10 keV, and an absorbed two temperature model to fit the entire spectrum between ~ 0.1 –10 keV. Both gave consistent results with each other for the central hard variable component. On the other hand, in an analysis of *ASCA* spectra obtained just prior to the 1997/98 minimum, Corcoran et al. (2000) fixed the emission from the outer ejecta using the model derived

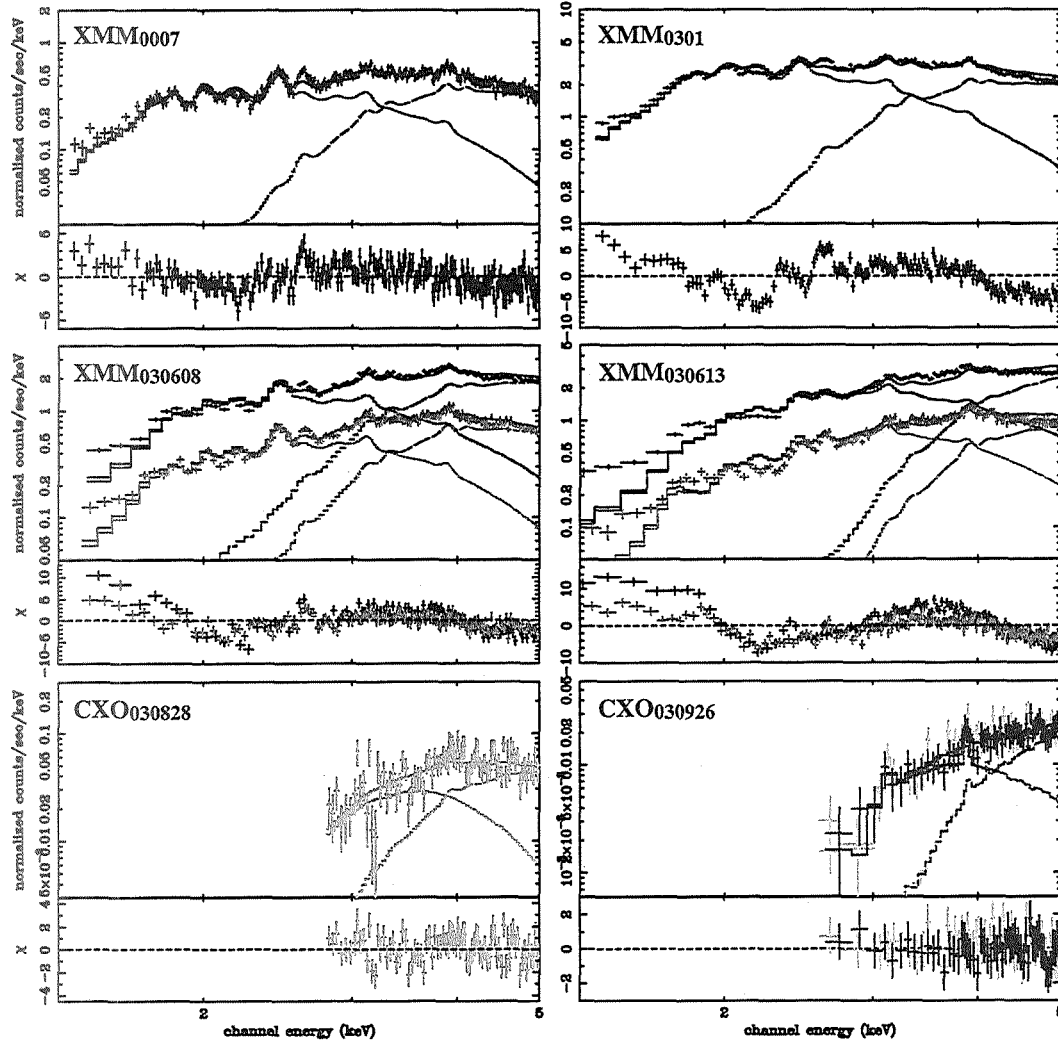


Fig. 9.— Fits of the spectra below 5 keV.

TABLE 6
ADDITIONAL SOFT COMPONENT FOR THE SPECTRUM BELOW 5 keV

Observation	ϕ_{orbit}	kT (keV)	Z (solar)	$\log E.M.$ (cm^{-3})	N_H (10^{22} cm^{-2})	Reduced χ^2 (d.o.f.)
XMM0007	0.470–0.471	1.1 (1.1–1.2)	0.25 (0.20–0.31)	58.3 (58.2–58.4)	5.4 (5.2–5.5)	2.04 (225)
XMM0301	0.922–0.924	1.1 (1.1–1.1)	0.18 (0.16–0.19)	58.8 (58.8–58.8)	5.4 (5.3–5.4)	8.85 (164)
XMM030608	0.988	1.1 (1.1–1.1)	0.24 (0.22–0.26)	58.6 (58.6–58.7)	6.9 (6.8–7.0)	5.41 (260)
XMM030613	0.990	1.6 (1.5–1.6)	0.25 (0.22–0.28)	58.6 (58.5–58.6)	7.7 (7.5–7.8)	12.02 (300)
CXO030828	1.028	0.5 (0.4–0.9)	<0.58	59.9 (58.1–60.1)	29 (17–39)	1.32 (80)
CXO030926	1.042	0.9 (0.6–1.8)	0.28 (0.05–0.75)	59.2 (58.0–60.5)	23 (13–33)	0.52 (109)

NOTE.—These fits refer to the spectrum after subtraction of the CCE and the Homunculus emission.

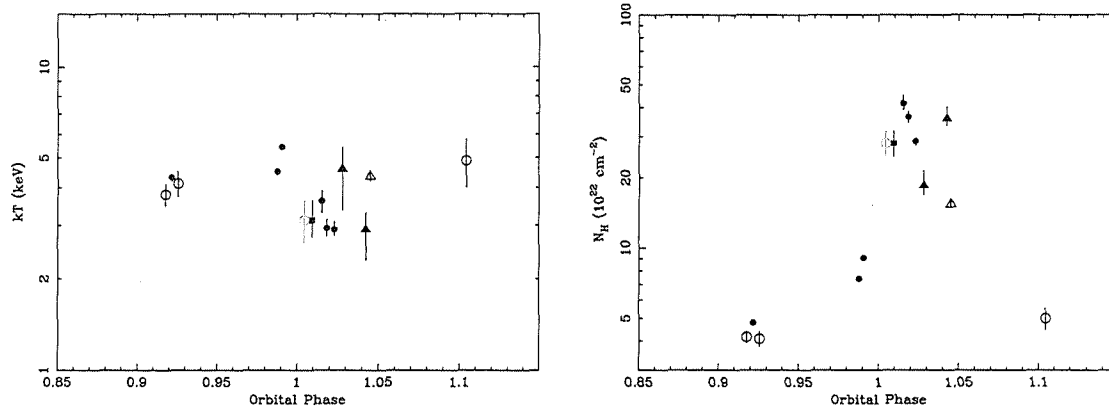


Fig. 10.— Variation of the temperature and absorption column ($N_{\text{H}}[\text{whole}]$) vs. orbital phase. The filled marks are from the 2003 cycle (circle: *XMM-Newton*, triangle: *Chandra*, square: simultaneous fit between *XMM-Newton* and *Chandra*). The open marks are from the 1997/98 cycle (circle: *ASCA*, triangle: *BeppoSAX*). The *ASCA* spectrum during the 2003 minimum at phase 1.004 is consistent with the N_{H} and kT values from CXOXM0307, as shown.

TABLE 7
OBSERVATIONS AROUND THE MINIMUM FROM PREVIOUS CYCLES

Abbreviation	Satellite	Date	P_{orbit}	Exposure (ksec)	N_{H} (10^{22} cm^{-2})	kT (keV)	Reference
ROSAT920612	ROSAT	1992 Jun. 12, 22:33	-0.998	23.6	...	...	...
ASCA970703	ASCA	1997 Jul. 3, 09:58	-0.082	12.6	4.16 ± 0.23	3.79 ± 0.31	1
ASCA970719	ASCA	1997 Jul. 19, 15:11	-0.074	12.8	4.09 ± 0.30	4.12 ± 0.39	1
ASCA971224	ASCA	1997 Dec. 24, 09:29	0.004	58.8	...	...	1
SAX980318	BeppoSAX	1998 Mar. 18, 05:01	0.045	39.0 ^a	15.4 ± 0.4	4.35 ± 0.15	2
ASCA980716	ASCA	1998 Jul. 16, 04:40	0.104	13.4	5.00 ± 0.52	4.89 ± 0.88	1

NOTE.— N_{H} and kT refer to the hottest components in 2-temperature fits of the entire spectra; *ASCA* results refer to analysis of the GIS2 spectra. Ref. 1: Corcoran et al. (2000), 2: Viotti et al. (2002)

^aExposure time for the MECS23 detector.

in Corcoran et al. (1998). Though the coolest temperature they used to fit the *ASCA* spectra ($kT \sim 0.3$ keV) is a bit lower than our adopted temperature ($kT \sim 0.6$ keV) and the resulting difference in the outer ejecta flux is about a factor of three at ~ 2 keV, this only produces a $\sim 1\%$ uncertainty in the flux of the variable emission outside the 2003 minimum. The results of their *BeppoSAX* and *ASCA* analyses, therefore, are comparable to the result we derived from our 1T fits to the entire *XMM-Newton* and *Chandra* spectra in §4.2.2.

The plasma temperatures in the 1997/98 observations were always around ~ 4 – 5 keV, which is similar to our results. The derived values of N_{H}

varied significantly with phase (Figure 10), reaching a maximum during the X-ray minimum, and declining thereafter. The variation in 2003 was similar to the N_{H} variation in 1997/98, except for the interval just at the end of the minimum. Though *BeppoSAX* and *Chandra* observed η Car at a similar orbital phase ($\phi_{\text{SAX980318}} \sim 0.045$, $\phi_{\text{CXO030926}} \sim 1.042$), the N_{H} measured with *Chandra* in 2003 is a factor of two larger than the value derived by Viotti et al. (2002) from the *BeppoSAX* observations in 1998. This is consistent with the behavior of the hardness ratio after the recovery as measured by *RXTE*, which was higher in the 2003 recovery than in the 1998 recovery (Corco-

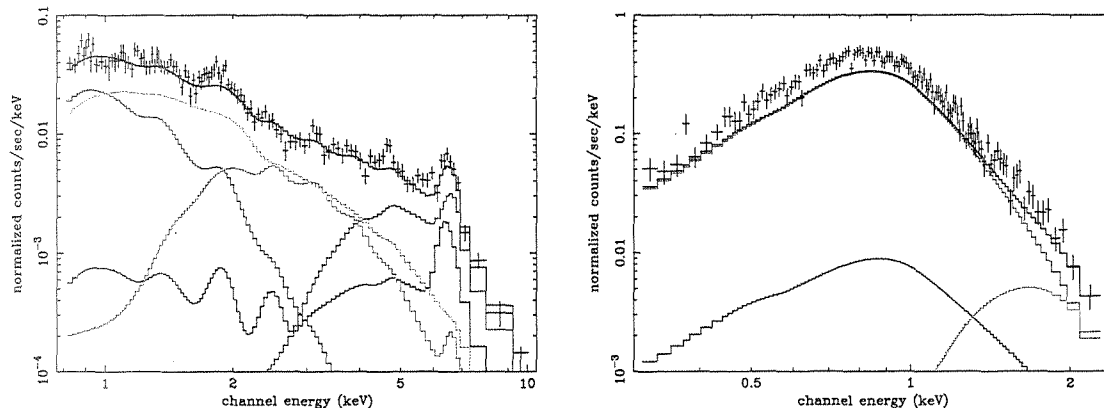


Fig. 11.— *Left*: ASCA GIS2+3 spectrum on 1997 Dec. 24. *Right*: ROSAT PSPC spectrum on 1992 Jun 12. In each plot the spectrum of η Car during the X-ray minimum in 2003 is shown (*red*: the outer ejecta, *blue*: X-ray Homunculus Nebula, *green*: CCE component, *purple*: variable emission in CXO XMM0307; *orange*: surrounding sources within 3'. The solid black line shows the sum of these emission components.

ran 2005).

5.2. Comparison of the 1997/98 and 2003 Spectra During the Minima

In order to compare this dataset with the X-ray observations during the 2003 minimum, we re-analyzed the ASCA₉₇₁₂₂₄ GIS data. We screened the “revision2” data taken from the HEASARC archive⁸ using *gisclean* and filtered it with the standard criteria, which excludes data affected by the South Atlantic Anomaly, Earth occultation and high background in regions with low geomagnetic rigidities. For both GIS2 and GIS3 detectors, we used a 3' radius circle centered on η Car as the source region “3' SRC”, and used as background emission from a 3' radius circle designated “3' BGD” centered to the north-east of η Car (Figure 2) where the soft diffuse X-ray emission from the Carina Nebula is apparently weak (Hamaguchi et al. 2006). We used the standard GIS response files, version 4.0 (g[23]v4.0.rmf) and generated ancillary response functions with *ascaarf* ver. 3.10. We then merged both GIS2 and GIS3 spectra together to improve signal to noise. The left panel of Figure 11 shows the GIS spectrum from ASCA₉₇₁₂₂₄.

Because the stellar source was faint during the minimum and the ASCA point spread function

is large, contamination by nearby X-ray sources is significant for this observation. We therefore tried to estimate the contamination from emission from sources within 3' of η Car “3' SRC” using XMM₀₃₀₇₂₂ (when the central point source of η Car was the weakest) excluding the source region “XMM SRC” used for the analysis of η Car from the XMM-Newton MOS2 data. We used the same background region as we used to estimate the ASCA background emission, “3' BGD”. About 10% of the emission from η Car (which amounts to $\sim 20\%$ of the emission from the surrounding sources even in XMM₀₃₀₇₂₂) contaminates the “3' SRC” region. We simulated the contamination due to η Car and subtracted it from the ASCA source spectrum. The subtracted spectrum (Figure 12) does not show any evidence of the extremely strong nitrogen line at ~ 0.5 keV from the outer ejecta, suggesting that contamination is well removed.

The resulting spectrum, after subtracting the simulated η Car spectrum, shows weak emission lines at ~ 0.9 and 1 keV from Ne IX and Ne X, ~ 0.8 keV possibly from Fe, and a marginal excess around ~ 3 –4 keV from Ca. This spectrum can be fit either by an optically thin, thermal (MEKAL) model with 2-temperature components or by a cool component plus a power-law component for the hard emission at slightly below the 90% confidence, assuming common absorption for

⁸<http://heasarc.gsfc.nasa.gov/W3Browse/>

TABLE 8
THE SPECTRAL FIT OF THE SURROUNDING REGION

Model	Soft Component		Hard Component		Z (10^{-1} solar)	N_H (10^{21} cm $^{-2}$)	reduced χ^2 (d.o.f.)
	kT (keV)	$\log E.M.$ (cm $^{-3}$)	kT (keV)	$\log E.M.$ (cm $^{-3}$)			
2T	0.24 (0.18–0.29)	57.7 (57.2–58.5)	2.6 (1.9–3.3)	56.2 (56.2–56.4)	0.36 (0.19–0.70) ^a	3.6 (2.6–5.5)	1.28 (92)
1T + pl	0.27 (0.23–0.30)	56.5 (56.3–56.8)	...	...	3 (fix) ^b	2.6 (2.1–3.3)	1.26 (93)
				2.5 (2.4–2.7)			

^aThe abundance parameters of both soft and hard components are tied together.

^bThe absorption is insensitive to abundance in the range between 0 and 10 solar.

NOTE.—Values in parentheses denote 90% confidence limits.

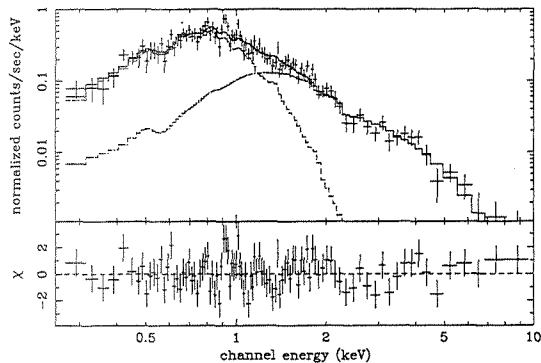


Fig. 12.— *XMM-Newton* MOS2 spectrum from XMM030722 extracted from a 3' radius circle excluding emission from η Car. The solid line shows the best-fit 2T MEKAL model with common absorption, while the broken lines show the individual fit components.

both components (Table 8). In either model, the average absorption to these sources is consistent with the interstellar value ($\sim 3 \times 10^{21} \text{ cm}^{-2}$, see §2.2 of Leutenegger et al. 2003). As the spectrum does not have strong emission lines, the elemental abundance of the 2T model is small (~ 0.04 solar), while the abundances are not constrained by the 1T plus power-law model. We thus fixed the abundances at 0.3 solar, a typical value for stellar X-ray emission obtained from low resolution CCD spectra (e.g. OB stars, Kitamoto & Mukai 1996; Kitamoto et al. 2000; low-mass MSs, Tagliaferri et al. 1997; low-mass PMSs, Yamauchi et al. 1996; Kamata et al. 1997; Tsuboi et al. 1998.)⁹ The observed flux is $\sim 3.2 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}$ (0.5–10 keV).

The “3' SRC” region includes at least 55 *Chandra* X-ray point sources (Evans et al. 2003): 6 OB stars and 49 unidentified, weak sources that might be low mass pre-main-sequence stars. The combined absorption corrected flux from these sources calculated from Table 3 and 4 in Evans et al. (2003) is $1.3 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}$ (0.5–2.04 keV). There is also diffuse emission

⁹High resolution grating spectra with *Chandra* and *XMM-Newton* showed complex line profiles especially from OB stars, and therefore the abundance obtained from low resolution spectra may not reflect real elemental abundance. (e.g., Cassinelli et al. 2001; Kahn et al. 2001; Miller et al. 2002)

within the source region which is also calculated from Evans et al. (2003) to have a flux of $\sim 5.7 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}$. The total absorption corrected flux, $\sim 7 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}$, is roughly consistent with our result $8.2 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}$ (0.5–2.04 keV, unabsorbed). Moreover, the combined absorption corrected fluxes of the point sources are as large as the flux from the hard component ($1.7 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}$), and the flux from the diffuse emission is as large as the soft component, $6.5 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}$, in the 0.5 – 2.0 keV band. As seen in Figure 2, many point sources are detectable at intermediate energies, where the hard component is dominant, but they are not clear in the soft band (except for HDE 303308). The hard component probably represents emission from point sources with the soft component dominated by diffuse emission and HDE 303308.

We have compared the *ASCA* spectrum to a model derived from our fits to the *Chandra* and *XMM-Newton* spectra including emission from the outer ejecta, from the Homunculus Nebula, from the CCE component and the variable model which fits the spectrum obtained from the CXOXMM0307 observation, along with emission from the surrounding sources (diffuse emission and point sources) which fall within the 3' extraction circle. The *ASCA* spectrum agrees well with this combined model. Assuming that emission from the outer ejecta, X-ray Homunculus Nebula and the surrounding sources did not vary between 1997 and 2003 and that spectral shapes of the CCE and variable components did not change dramatically, the flux of both CCE and variable components are the same within 50%.

5.3. Comparison with the 1992 Minimum

There is one *ROSAT* PSPC observation of η Car during the minimum in mid-1992. Corcoran et al. (1995) used this observation to show that the X-ray emission in the hard *ROSAT* band ($E > 1.6 \text{ keV}$) decreased by a factor of 2 at that time. *ROSAT* however had very little effective area above 2 keV so that the bulk of the variable emission was not observable by *ROSAT*.

Corcoran et al. (1995) extracted a spectrum from a 1.85 radius circle excluding a 30" radius circle around the nearby bright star HDE 303308. To minimize contamination from surrounding

sources, we re-extracted the spectrum using an elliptical source region of $65'' \times 47.''5$, which includes emission from the outer ejecta but which excludes HDE 303308 and point and diffuse sources around η Car. We took the same background region as used in our analysis of ASCA₉₇₁₂₂₄. In analyzing the PSPC spectrum, we used the standard response file `pspcb_gain2.256.rmf` from the *ROSAT* calibration database, but we generated the ancillary response file using the `pcarf` v. 2.1.3 as appropriate for this observation.

The PSPC spectrum is shown in the right panel of Figure 11. We have overlaid all the spectral components of η Car on this spectrum as we did for the ASCA₉₇₁₂₂₄ spectrum, except for the component due to the surrounding sources, whose contribution would be small in the *ROSAT* spectrum due to the smaller PSPC extraction region. Emission between 0.5–1 keV, where the outer ejecta component is dominant, is about a factor of 30% larger than the model. This difference may be due to calibration uncertainties between *ROSAT* and *XMM-Newton*, or it might be produced by another variable source within the *ROSAT* extraction area. Though the *XMM-Newton* model of the CCE component only contributes to the few highest channels of the PSPC detector, this component is consistent with the *ROSAT* spectrum. Thus it appears that *ROSAT* did not detect the stellar component at all during the 1992 minimum.

6. Discussion

6.1. Emission from the Variable Component

RXTE clearly showed that the variable emission is periodic and leaves little doubt that the emission is produced by the WWC in a binary system (Corcoran 2005), and if so, that the X-ray minimum occurs near periastron passage. Our results further strengthen this conclusion. The temperature of the hottest plasma, ~ 3 keV, was mostly unchanged through the cycle, consistent with the collision of stellar winds at terminal velocities (e.g., see Ishibashi et al. 1999). Furthermore, the spectral shape varied in a periodic way, as well. However, the N_H measured just after the end of the X-ray minimum was about a factor of two larger during the 2003 cycle than it was during

the 1998 cycle.

Most of the light curves derived from the *Chandra* and *XMM-Newton* data showed no short-term variations, suggesting that the X-ray plasma is produced by a steady source and is probably larger than $V_{shock} \times t_{exp}$, where V_{shock} is the pre-shock velocity and t_{exp} is the exposure time of the observation. For $V_{shock} \sim 3000$ km s $^{-1}$ (corresponding to shock temperatures of $\sim 3 - 4$ keV) and exposure times of ~ 10 ksec (corresponding roughly to the *XMM-Newton* observing time), the size of the emitting region is probably $\gtrsim 0.2$ AU, and perhaps considerably larger. The *RXTE* lightcurve also shows clear variations in observations separated by as little as 1 day, suggesting that the size of the emitting region is $0.2 \lesssim r \lesssim 2$ AU. Although the orbital elements are currently uncertain, the stellar separation at periastron may be as little as 1.5 AU (Corcoran et al. 2001a), so that the size of the emitting region may be comparable to the stellar separation at periastron passage.

Spectra outside the 2003 minimum require at least 2 temperatures, $kT \sim 3$ keV and 1–1.5 keV, consistent with the analysis of a *Chandra* grating spectrum by Corcoran et al. (2001b). The failure to fit most of the spectra by 2 temperature models in §4.2.4 is perhaps an indication of the presence of more than 2 temperatures. This is consistent with a hydrodynamic simulation of the WWC plasma (Pittard & Stevens 1997), in which the plasma temperature is the highest near the stagnation point where the winds collide head-on, and cooler farther along the bow-shock. The excess at the blue side of the Fe XXV line discussed in §4.2.3 may represent streams from the stagnation point flowing outward near the companion’s wind terminal velocity.

The *RXTE* light curves also displayed quasi-periodic X-ray “flares”, which correspond to hardness ratio maxima (Corcoran et al. 1997; Corcoran 2005). XMM₀₃₀₆₀₈ occurred near the bottom of one of these flares, while XMM₀₃₀₆₁₃ occurred near a flare peak. A comparison of these spectra in Figure 7 shows that the hard band flux went up by a factor of two, while the soft band flux below ~ 3 keV did not change except that emission lines are apparently weaker in XMM₀₃₀₆₁₃. This is consistent with an increase of the hardness ratio measured with *RXTE*. This indicates either a slight increase in kT and/or $E.M.$ for the hottest

plasma, possibly caused by increase of the density of the high-temperature gas near the stagnation point, as discussed for a similar event in the previous cycle observed with *ASCA* (Corcoran et al. 2000). The emission at $E \lesssim 3$ keV, on the other hand, did not vary strongly between those observations. One possibility is that hard X-ray emission from the highest-temperature plasma at the stagnation point of the shock cone varied strongly due to density fluctuations of the primary or secondary wind, with the soft X-ray emission coming from a larger area which averages out such fluctuations. Another possibility is that the flares are related to instabilities in the WWC plasma.

6.2. The Absorber around the WWC Plasma

Before the 2003 minimum, N_H measured from our fits to the spectra above 5 keV (hereafter $N_H[>5 \text{ keV}]$) was always about a factor of four larger than N_H measured from the spectra below 5 keV ($N_H[<5 \text{ keV}]$; Figure 13). $N_H[>5 \text{ keV}]$ mainly represents Fe absorption, while $N_H[<5 \text{ keV}]$ represents absorption by lighter elements (Morrison & McCammon 1983). Though this discrepancy can be produced by an Fe overabundance in the η Car ejecta, the elemental abundances around the stellar source are near solar except for He and N, which are overabundant, and O and C, which are strongly depleted (Hillier et al. 2001; Verner et al. 2005; Davidson et al. 1984). Abundance anomalies of He, N, O and C would not change the amount of absorption above ~ 1 keV. This means that the soft emission does not suffer as strong absorption as the hard emission before the minimum, and hence this supports the idea that the variable emission originates in multiple-temperature plasmas with various absorptions. This is consistent with the idea that the hot emission originates from a highly absorbed region near the apex of the shock cone, with the lower-energy emission arising from a region farther along the shock interface which suffers less absorption. Neither $N_H[>5 \text{ keV}]$ nor $N_H[<5 \text{ keV}]$ varied significantly between XMM0007 at $\phi \sim 0.47$ (close to apastron) and XMM0301 at $\phi \sim 0.92$, when the stellar separation changed by about a factor of 3. The value of $N_H[<5 \text{ keV}]$ before the minimum ($\sim 5 \times 10^{22} \text{ cm}^{-2}$) may be absorption beyond the wind of the primary. The higher value of

$N_H[>5 \text{ keV}]$ suggests that extra absorbing material must be located near the hottest plasma.

After XMM0301 and through the onset of the 2003 minimum, $N_H[>5 \text{ keV}]$ and the absorption column derived from fitting the spectra over the entire 1–10 keV band ($N_H[\text{whole}]$, see Figure 10) increased to $3\text{--}5 \times 10^{23} \text{ cm}^{-2}$. As shown in Figure 10 the observed maximum column density occurred near the mid-point of the X-ray minimum, and the column densities declined thereafter towards the end of the minimum. During the X-ray minimum, $N_H[<5 \text{ keV}]$ was unmeasurable because of the near total suppression of the low energy flux. This could mean that the *E.M.* of the cool component decreased during the minimum, or that the absorption to the cool plasma also increased on the line of sight. Nevertheless, the $N_H[>5 \text{ keV}]$ confirms that the X-ray minimum is closely associated with an increase in the amount of absorption along the line of sight. This suggests that the WWC plasma entered into, or was hidden behind, the densest part of wind from the primary star. The behavior of the absorption towards the hard component, $N_H[>5 \text{ keV}]$, is in interesting contrast to the behavior of $N_H[\text{whole}]$. $N_H[>5 \text{ keV}]$ had already increased to $\sim 4 \times 10^{23} \text{ cm}^{-2}$ by XMM030613 (i.e. prior to the start of the X-ray minimum) and it did not change strongly after that. This could be explained if the WWC region was bent, perhaps by the Coriolis force, causing the stagnation point to enter into the densest part of the primary's wind earlier than the downstream material.

The column density did not decline until some time after the 2003 minimum ended. This confirms that the column density variation is not completely synchronous with the X-ray minimum. Conjunction probably occurred during the interval when N_H was near its maximum observed value, in the phase interval $0.99 < \phi < 1.05$. We note that the N_H measured in 2003 ($\phi=1.042$) is a factor of two larger than the N_H measured in 1998 ($\phi=0.045$). Davidson et al. (2005, see their Figure 2c) also noted that the absorption component in the P- η ($\lambda 9017$) line in 2003.72 ($\phi \approx 1.0$) was stronger than in 1998.21 ($\phi \approx 0.0$), which might also indicate that the amount of absorbing material in the line of sight near the start of the X-ray minimum is increasing with time. However they also note that the equivalent widths of the H- α emission lines were lower just after the end of the

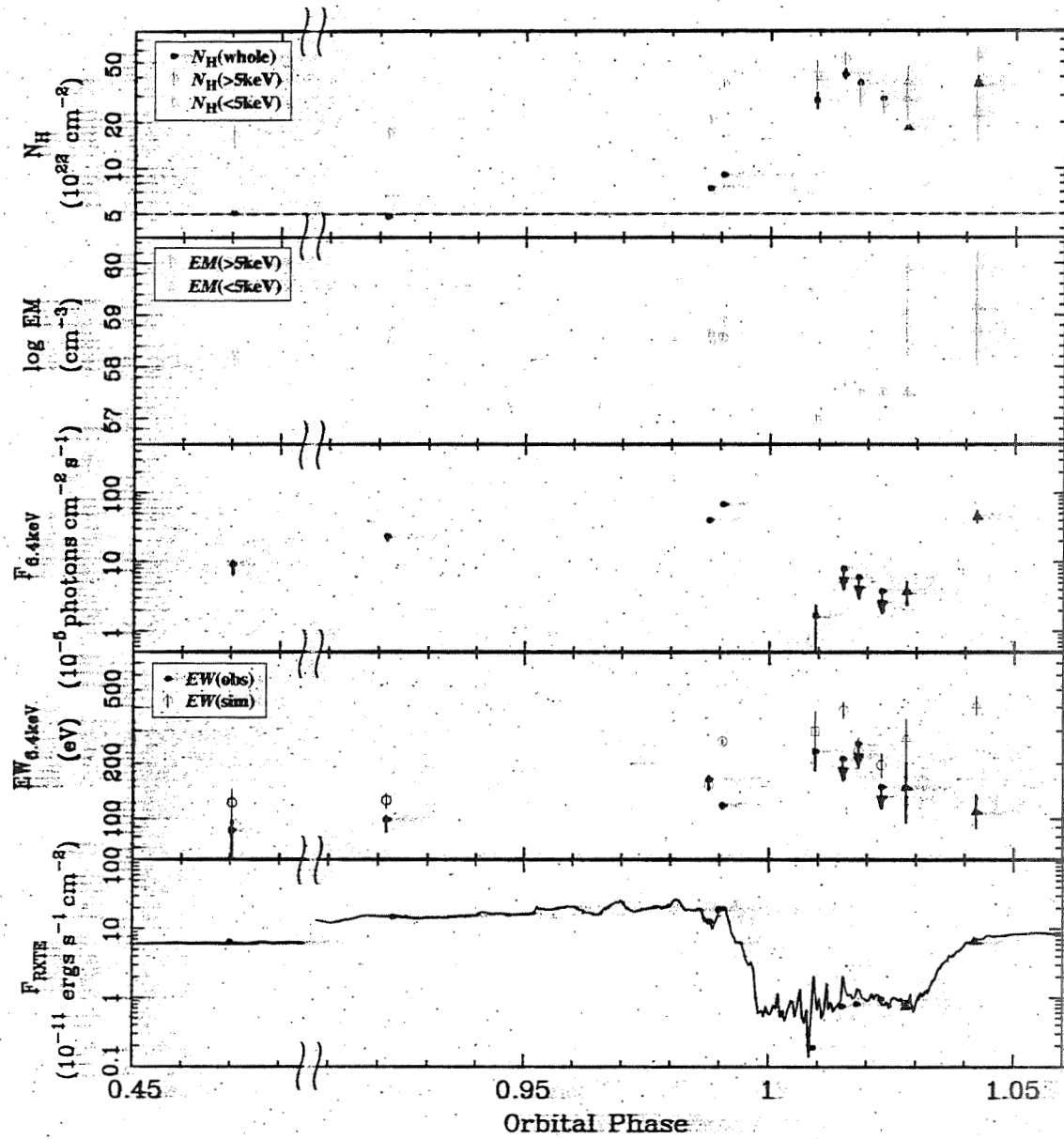


Fig. 13.— Variation of N_H , $E.M.$, intensity and EW of the Fe fluorescence line and $RXTE$ flux in the 2003 cycle. The *XMM-Newton* results are shown as circles, *Chandra* results as triangles, while squares show results derived from a simultaneous fit between *XMM-Newton* and *Chandra*. The dash line in the top panel represents our estimate of the absorption beyond the central source.

2003 minimum. This might suggest a distribution of wind material which has preferentially grown denser in the line of sight than perpendicular to the line of sight in the 1998–2003 interval.

The equivalent width (EW) of the Fe K fluorescence line varied between 100–200 eV, which is far smaller than the EW (~ 1.5 keV) produced by scattering X-rays from the Homunculus Nebula (Corcoran et al. 2004). This suggests that the X-ray emission in all the observations comes directly from the WWC plasma, even during the X-ray minimum, with only a small scattered component (see Figure 14). From Inoue (1985), the Fe K fluorescence line EW produced by scattering from a spherically-symmetric medium around an X-ray source is $EW \sim 7.5 \times N_H[>5 \text{ keV}]/10^{22} \text{ eV}$, where we have multiplied Inoue’s coefficient by 0.75, the flux ratio in the 7.1–9 keV band between a $kT \sim 3.3$ keV thermal emission component appropriate to the η Car spectra and the $\Gamma = 1.1$ power-law emission component assumed by Inoue (1985). In Figure 13, we plot the expected Fe-K fluorescence line EWs as open symbols for a spherically-symmetric scattering medium. The differences between the expected and observed equivalent widths seem to be larger when the X-ray flux goes up and smaller when it goes down (XMM030608, XMM030613 and CXO030926), which may suggest that the variation of the fluorescence line is delayed by light travel time.

The observed EWs are $\sim 25\%$ smaller than the expected EWs even during the XMM0007 ($\phi=0.470$) and XMM0301 ($\phi=0.923$) observations when the direct X-ray emission did not vary strongly. This suggests that the scattering material is not spherically symmetric as assumed in Inoue (1985), and that there is a deficit of scattering material off the line of sight. This deficit is probably produced by the wind-wind collision, since the region on the companion side of the shock has a much lower density than on the primary star’s side. In order to reduce the fluorescent Fe emission by 25%, the full opening angle of the wind shock cone would need to be $\sim 120^\circ$. This is consistent with the measurement of the half-opening angle of $50 - 120^\circ$ by Pittard & Corcoran (2002).

6.3. The Nature of the X-ray Minimum

The 2003 X-ray minimum can be described as an apparent decrease in EM , along with an increase in N_H . However, a column density of $N_H \sim 5 \times 10^{24} \text{ cm}^{-2}$ is needed to reduce the emission at 10 keV by two orders of magnitudes, and the observed maximum column density ($N_H \sim 5 \times 10^{23} \text{ cm}^{-2}$) is much lower than this. The ASCA observations during the 1997/98 minimum (Corcoran et al. 2000) also appeared consistent with an apparent decline in EM .

Two mechanisms could produce the observed decrease in EM . One possibility is an “eclipse model”, namely that emitting region is almost totally, but not completely, obscured by an optically thick absorber with $N_H \gtrsim 10^{25} \text{ cm}^{-2}$, and we only see the least absorbed residual emission during the minimum. Ishibashi et al. (1999) and Corcoran et al. (2001a) tested the eclipse model using the RXTE light curve of η Car and showed that the duration of the X-ray minimum (~ 3 months) at high energies ($E > 5$ keV) was difficult to explain for a spherically symmetric wind from η Car if the mass loss rate was constant at $\sim 10^{-4} M_\odot \text{ yr}^{-1}$. The eclipse model seems to require that the wind is not spherically symmetric, or that the absorption to the hard X-ray emitting region was enhanced for an extended interval near periastron passage. It also suggests that a portion of the hard emission is visible during the minimum so that the size of the hottest region is greater than the size of the occulting region.

Another possibility is that the emissivity of the WWC itself fades during the minimum, i.e. that there is a decline in the amount of material hot enough to generate ~ 5 keV X-rays. Some WWC models predict a change in the X-ray emissivity of the shock around periastron. For example, “radiative braking” (Gayley et al. 1997) in which UV photons from η Car decelerate the companion’s wind at phases near periastron could reduce the intrinsic X-ray emission from the wind-wind collision at $E > 5$ keV. Davidson (2002) suggested that strong instabilities near periastron might cause the shocked gas to radiatively cool, reducing the emission at high energies. Soker (2005) and Akashi et al. (2006) suggested that Bondi-Hoyle accretion of the primary star’s wind by the companion star near periastron could suppress the compan-

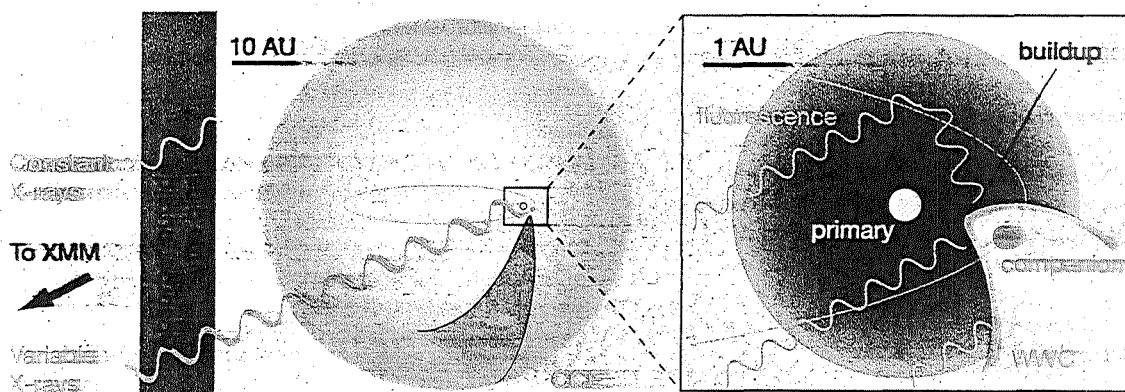


Fig. 14.— Cartoon of the η Car system: Winds from the primary star and the companion collide together, to form the wind-wind collision (WWC) region which has a conical shape. Behind the WWC boundary is a low density region filled with the wind of the companion star. The apex where the winds collide head on has hotter gas than the downstream material and also accumulates a buildup of cool primary wind material in front. We view the X-ray emission from the WWC plasma through the cool material at the apex and/or the undisturbed primary wind, and the absorber which lies far outside the binary system. Iron K fluorescence emission is produced by scattering in the primary wind. One possibility for the CCE, where the CCE is produced in outer shock, is shown. Emission from the CCE only passes through the outer absorber beyond the binary system.

ion's wind and thus reduce the emission from the colliding wind shock for a brief period. In optical observations, the He II $\lambda 4687$ emission line, which is believed to arise near the WWC shock, decreased in concert with the X-ray drop (Steiner & Damineli 2004). Martin et al. (2006) argued that the disappearance of this line in a direct view of the star, and in a reflected polar view (the so-called "FOS4" position, Stahl et al. 2005) indicated a waning of the shocked gas during the minimum.

Below, we examine some of the behaviors of the electron temperature, iron line profile, iron fluorescence line variation and lack of variation at $E > 7$ keV during the minimum from the 2003 X-ray spectra to try to decide between these two mechanisms.

6.3.1. Electron Temperature

The electron temperature of the hottest material did not change significantly during the 2003 minimum, as the normalized spectra at the bottom of Figure 7 clearly show. The constancy of the electron temperature of the hottest material argues against radiative braking, shock instabil-

ity or accretion models which predict that the plasma temperature should decrease. Akashi et al. (2006)'s model in particular predicts complete shutdown of the WWC activity during periastron passage, and therefore could only be consistent with a constant electron temperature if an alternative X-ray emission mechanism during the minimum could produce plasma at nearly the same temperature as the WWC emission. If the shock actually disappears during the minimum, then the constancy of the high-energy X-ray continuum requires that a small part of the 3000 km s^{-1} secondary wind continues to produce a shock by encountering material directly at normal incidence.

6.3.2. The Iron Line Profile

The variable excess emission on the red side of the Fe XXV line can be explained by non-equilibrium ionization (NEI) effects in the high-temperature plasma, and variations in the strength of this feature means that the ion temperature of some of the high-temperature plasma in the colliding wind shock changed during the minimum. This might favor mechanisms in which the intrinsic emission from the shock declines with

time near periastron, though the NEI effect itself does not reduce emissivity of the continuum. The observed excess at ~ 6.55 keV is consistent with emission lines of around Fe XXI, present at an ionization time scale $\tau = nt \sim 10^{10-11}$ s cm $^{-3}$ in the ~ 3.3 keV plasma, where n is the gas density and t is the time after the gas starts heating. Since the gas density $n \propto D^{-2}$, it should be larger by more than two orders of magnitude at periastron than at apastron (using the orbital elements of Corcoran et al. 2001a). Thus near periastron the plasma should reach ionization equilibrium much faster (~ 15 min, Soker 2005) than at apastron. Perhaps near periastron, both the cooling time-scale and the equilibrium time-scale decrease relative to their values at apastron, but the cooling time-scale decreases faster. This means that near periastron the fraction of non-equilibrium gas to gas in equilibrium is larger than it is near apastron. However, since the radiative cooling time-scale has the same dependence on gas density as the ionization equilibrium time-scale ($\propto n^{-1}$), an additional cooling mechanism (such as adiabatic expansion or conduction) needs to be effective near periastron in order to decrease the cooling time-scale faster than the equilibrium time-scale.

6.3.3. Iron Fluorescence Line Variations

As noted in the previous section, the EWs of the Fe K fluorescence line stayed below ~ 200 eV during the 2003 minimum, and therefore the observed X-ray emission is direct emission, with only a small scattered component. The Fe fluorescence line flux decreased by a factor of ~ 50 during the 2003 minimum (Figure 13). This could be produced by reducing the number of $E > 7.1$ keV X-ray photons from the source seen by the fluorescing region, or by reducing the number of photons from the fluorescing region which reach the observer. If we assume that the fluorescing region extends far from the stars then during the 2003 minimum either the X-ray source is nearly entirely covered by obscuring material along the line of sight to the fluorescing region, or the intrinsic X-ray emissivity has declined so that fewer ionizing photons reach the fluorescing medium. This picture is consistent with a similar variation of He II $\lambda 4687$ emission between the direct emission from the central WWC region and polar emission scattered from the SE lobe (Stahl et al. 2005; Martin et al. 2006).

6.3.4. The Lack of Variation at $E > 7$ keV During the Minimum

The hard band X-ray emission above ~ 7 keV reached its lowest value after the 2003 minimum started, recovered by a factor of 3 after XMM030722 and did not vary for at least ~ 3 weeks from XMM030802 to CXO030828. Since *RXTE* light curves showed a similar trend in the previous cycle, the time variation seems to be phase repeatable. The observed X-ray flux after XMM030722 was $\sim 5\%$ of the flux at XMM030613. It is very difficult for an eclipse of the X-ray emitting region by an opaque disk (similar to that proposed by Ishibashi et al. 1999, for example), to keep the observed flux constant for so long a time, since the stellar motion would be so fast near periastron that the emitting region moves beyond the occulter on \sim day timescales, causing a short eclipse and a rapid rise in X-ray brightness. Perhaps a “leaky absorber” eclipse, in which the absorbing medium is very extended and composed of optically thick clumps, could better describe the behavior of the observed flux during the minimum. Models in which the shock cools may not be consistent with the constancy of the $E > 7$ keV emission either, unless some residual emission at high energies could be generated after the shock cools.

6.4. The Origin of the CCE Component

The CCE component did not vary within the two months during the 2003 minimum when it could be observed. It apparently had the same spectrum during the 1998 minimum (as shown by our analysis of ASCA971224), and did not show any enhanced emission during the minimum in 1992. This suggests that the X-ray source is stable on time-scales of 5–10 years. The *Chandra* image during the 2003 minimum restricts the size of the emitting plasma to $\lesssim 1''$, constraining the maximum size of the CCE at $\lesssim 2000$ AU. The column density to this component, $N_H \sim 5 \times 10^{22}$ cm $^{-2}$, is smaller than the column density to the variable emission component around the 2003 minimum, but each component shows nearly the same column density in January 2003 (before the 2003 minimum) and near apastron. After correcting for absorption, the X-ray luminosity of the CCE is $\sim 10^{34}$ ergs s $^{-1}$. This suggests that a stable luminous source is present outside of the absorbing

material which lies in front of the colliding-wind source at periastron.

One possibility is that the CCE component is produced within the wind of the companion star and/or η Car due to the inherent instabilities of their radiatively-driven winds. The X-ray properties of the CCE component – $kT \sim 1$ keV with little apparent X-ray variation – resemble the X-ray properties of normal OB stars (e.g., Berghöfer et al. 1997; Corcoran et al. 1993). For OB stars $\log L_X/L_{\text{bol}} \approx -6$ to -8 (Berghöfer et al. 1997), so that the X-ray luminosity of the CCE corresponds to a bolometric luminosity $L_{\text{bol}} \sim 10^{40-42}$ ergs s^{-1} . This is somewhat larger than the luminosity of the companion according to Verner et al. (2005) ($L_{\text{bol}} \sim 4 \times 10^{39}$ ergs s^{-1}), but near the luminosity of η Car ($L_{\text{bol}} \sim 2 \times 10^{40}$ ergs s^{-1} , Hillier et al. 2001).

Alternatively, the CCE emission could be produced in ambient gas shocked by a strong outflow from the stellar winds (see Figure 14). The maximum size of the CCE ($r \lesssim 2000$ AU) means that it is inside the Little Homunculus nebula (Ishibashi et al. 2003), so that the CCE component might be produced by the collision of the polar wind from η Car with the Little Homunculus. The velocity of the polar wind from η Car is believed to be $v \sim 1000$ km s^{-1} (Smith et al. 2003a), which is sufficient to heat gas to $kT \sim 1$ keV. If all the kinetic energy of this outflow is converted to thermal energy, the required mass loss rate would have to be only $\sim 3 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ in order to match the observed emission measure ($\sim 7.0 \times 10^{56} \text{ cm}^{-3}$), which is only $3 \times 10^{-4} - 3 \times 10^{-5}$ of the mass loss rate of η Car ($\sim 10^{-3} - 10^{-4} M_{\odot} \text{ yr}^{-1}$, Hillier et al. 2001; Pittard & Corcoran 2002). The gas density inside the shell structure of the Little Homunculus should be less than the density of the shell, which is $10^6 < n_{\text{H}} < 10^7 \text{ cm}^{-3}$ (Ishibashi et al. 2003). Assuming that radiative cooling dominates, the cooling timescale of the plasma is $\tau \sim 3nkT/n^2\Lambda(T)$, where $\Lambda(T)$ is the emissivity. With a plasma density of $n < 10^7 \text{ cm}^{-3}$, and plasma temperature $kT \sim 1$ keV, and $\Lambda(1\text{keV}) \sim 3.1 \times 10^{-23} \text{ ergs s}^{-1} \text{ cm}^3$, then $\tau > 0.5$ years, consistent with our result.

A third alternative is that the CCE might be associated with the outflowing material from the WWC that collides with cold circumstellar gas and is reheated. The required mass loss rate streaming out through the WWC is given by $\dot{M} =$

$2L_X/\epsilon V^2 \sim 10^{-8}/(\epsilon \times (V/2000 \text{ km s}^{-1})^2) M_{\odot} \text{ yr}^{-1}$, where ϵ is the efficiency to convert the kinetic energy to X-ray emission, and V is the velocity of the outflow, which should be $\gtrsim 1,000$ km s^{-1} from the CCE temperature. Since the most of the companion's wind goes into the shock cone, the \dot{M} of the outflowing material should be $\sim 10^{-5} M_{\odot} \text{ yr}^{-1}$ (Pittard & Corcoran 2002), and ϵ should only be $\sim 0.1\%$.

7. Conclusions & Summary

We have observed η Car at key phases around the X-ray minimum in 2003 using the *XMM-Newton* and *Chandra* satellites and studied the variation of the X-ray spectral shape. We also compared the behavior of the X-ray emission during the 2003 minimum with observations during earlier minima made by *ASCA*, *BeppoSAX* and *ROSAT*. The results are summarized as follows.

1. During the minimum, the hard and medium band emission from the central point source decreased to 1–5% of the flux outside the minimum, but the emission did not disappear. The X-ray flux varied in an apparently stepwise way near the middle of the minimum, suggesting that the X-ray minimum has two states. The light curve within any single observation did not show significant variability on timescales of a few ksec, supporting that the hard X-ray emission is produced in a WWC.
2. The spectrum of the variable emission component changed markedly throughout the X-ray minimum. The medium band emission decreased gradually relative to the hard emission. Assuming an absorbed 1T model for the entire spectrum, the absorption to the central source increased from $5 \times 10^{22} \text{ cm}^{-2}$ to $4 \times 10^{23} \text{ cm}^{-2}$. The hard band flux went up prior to the X-ray minimum, and decreased abruptly during the 2003 minimum, without changing the spectral slope significantly, suggesting that the plasma electron temperature is constant around 3 keV.
3. The line flux ratios between the helium-like ions and hydrogen-like ions of Si, S, and Fe seen in the spectra before the 2003 minimum

indicate a similar type of multi-temperature plasma as seen near apastron by Corcoran et al. (2001b).

4. The values of N_H derived from the spectra above 5 keV ($N_H[>5 \text{ keV}]$) are larger than those values of N_H derived from the entire spectra ($N_H[\text{whole}]$) or from the spectra below 5 keV ($N_H[<5 \text{ keV}]$), but show less variation than $N_H[\text{whole}]$ or $N_H[<5 \text{ keV}]$. This suggests that the hotter plasma has stronger absorption, i.e. emission from η Car is multi-temperature, and each emission component is associated with an independent absorption component. This means that the hotter and cooler emission originate in spatially distinct regions. The hardest emission, which is believed to arise from material near the stagnation point of the WWC region, perhaps shows the effects of a build-up of material as the colliding wind shock plows through the primary wind.
5. The Fe XXV line profile showed a small blue excess, and a strong red excess before the 2003 minimum. The blue excess may be due to Doppler shifting of the line centroid or line broadening, and if so, the observed velocity is $\sim 4000 \text{ km s}^{-1}$. The red excess may indicate that some of the plasma is no longer in ionization equilibrium. The line showed a stronger red excess during the 2003 minimum than outside the minimum, which we interpret as decrease in the cooling time scale of the plasma near periastron. Interestingly, we note that an outburst spectrum of the dwarf nova SS Cyg taken with the *Suzaku* satellite showed a similar red excess on the Fe K line profile accompanied with a decrease in the hard band X-ray flux (Ishida et al. 2007).
6. We find evidence for a hard tail at $E > 9 \text{ keV}$, at about an order of magnitude larger than the background level, in spectra outside the X-ray minimum. This either indicates the presence of very hot plasma in the system or non-thermal emission perhaps produced by first-order Fermi acceleration of particles which then Compton-upscatter UV seed photons from the stellar photospheres and/or X-ray photons from the shock.
7. The values of N_H and kT of the X-ray spectrum at corresponding phases in previous cycles are very similar to those during the 2003 cycle, except during the recovery phase. In particular, the *ASCA* spectrum during the 1997/98 minimum (*ASCA*₉₇₁₂₂₄) is almost identical to the spectrum from *CXO*XMM₀₃₀₇. The difference in N_H during the recovery, as measured by *Chandra* and *BeppoSAX* could be produced by an increase in the density of the wind from η Car.
8. The EWs of the Fe fluorescence line at 6.4 keV are always below the values expected from $N_H[>5 \text{ keV}]$ assuming a spherically symmetric absorber. This is probably because the absorber is not spherically symmetric and is consistent with the lack of scattering matter in the lower-density wind of the companion if the full opening angle of the shock cone is $\sim 120^\circ$, consistent with the value derived by Pittard & Corcoran (2002).
9. The X-ray minimum is caused by the apparent decrease of the plasma *EM*. An eclipse model seems to explain the observed constancy of the plasma electron temperature, while the small EWs of the Fe fluorescence line and the deformation of the Fe XXV He-like triplet might indicate a real decline in the amount of hot gas in the colliding wind shock. It might also indicate that nearly all of the shock is hidden by an optically thick but slightly porous stellar wind.
10. We discovered a constant emission (CCE) component very near the central X-ray source. The CCE component can be seen between 1–3 keV during the X-ray minimum; at other times the emission from the colliding wind source overwhelms it. This component showed no variation on either short timescales within any observation or between observations for about two months during the 2003 minimum, and was apparently the same during the 1997/98 and 1992 minima. The CCE spectrum exhibited emission lines of Si XIII and S XIV, and can be fit by an absorbed 1T model with $N_H \sim 5 \times 10^{22} \text{ cm}^{-2}$, $kT \sim 1.1 \text{ keV}$ and absorption corrected $L_X \sim 10^{34} \text{ ergs s}^{-1}$. *Chandra* data suggest that the emission is point-like,

restricting the size of the source $\lesssim 2000$ AU at 2.3 kpc. This emission might be produced by collisionally-heated shocks from the fast winds from η Car or perhaps the fast moving outflow from the wind-wind collision with the ambient gas, or might be associated with shocked gas which is intrinsic to the wind of η Car.

11. X-ray emission within $3'$ from η Car can be reproduced by 2 emission components with interstellar absorption: cool plasma with $kT \sim 0.25$ keV (perhaps coming from the diffuse emission and HDE 303308), and hot plasma with $kT \sim 2.6$ keV or power-law $\Gamma \sim 2.5$, perhaps coming from a cluster of young stars. Correcting for these emission components is important in understanding the X-ray spectrum of η Car derived from lower spatial resolution X-ray observatories like *ASCA* and *Suzaku*.
12. Emission from the outer ejecta did not vary significantly on timescales of several years. The slope of the highest energy emission associated with the spectrum of the outer ejecta can be reproduced with $kT \sim 0.6$ keV, which is consistent with the highest temperature derived from analysis of the emission line spectrum (Leutenegger et al. 2003).

Currently, there are few reasons to suspect that the variable X-ray emission is not driven by shocks produced by the WWC from binary stars. For the first time, the spatially-resolved observations of η Car obtained by *XMM-Newton* and *Chandra* has revealed the details of the plasma and absorption components which are directly associated with the WWC plasma. While the earlier spectral analysis of Pittard & Corcoran (2002) did not account for the different emission components identified in this work, their fit was largely determined by emission above 2 keV which we have shown is dominated by emission from the WWC at the phase of their analysis.

Still the biggest mystery is the cause of the X-ray minimum, which is difficult to fully explain by occultation by a smooth wind from the primary star. If the X-ray activity really switches off during the minimum, a fading of the X-ray emission can be imaged in principle using the scattered X-

ray emission from the Homunculus Nebula. The intensity of the Fe K-shell fluorescence line just after the onset of the 2003 minimum should change differently between the eclipsing model and the fading model, and perhaps detailed monitoring of this line by spatially resolved X-ray spectral observations could decide the issue. On the other hand, deformation of the Fe XXV line profiles is unusual in the context of stellar systems, though similar deformation has been noted in iron lines arising from regions of strong gravity near black holes. This feature requires further study with high resolution spectrometers such as an X-ray microcalorimeter to produce sufficient spectral resolution at 7 keV.

We are grateful to A. Pollock, K. Koyama, K. Misaki and K. Mukai for useful comments. We greatly appreciate the *XMM-Newton* and *Chandra* review committee's positive response for the TOO observation proposal. This work is performed while K.H. held awards by National Research Council Research Associateship Award at NASA/GSFC, and supported by *Chandra* US grant (No. GO3-4008A). This research has made use of NASA's Astrophysics Data System. This research has made use of data obtained from the High Energy Astrophysics Science Archive Research Center (HEASARC), provided by NASA's Goddard Space Flight Center.

Facilities: *XMM-Newton*(EPIC), *CXO*(ACIS-S, HETG), *ASCA*(GIS), *ROSAT*(PSPC-B)

REFERENCES

- Akashi, M., Soker, N., & Behar, E. 2006, *ApJ*, 644, 451
- Anders, E., & Grevesse, N. 1989, *Geochim. Cosmochim. Acta*, 53, 197
- Aschenbach, B., Briel, U. G., Haberl, F., Bräuninger, H. W., Burkert, W., Oppitz, A., Gondoin, P., & Lumb, D. H. 2000, in *SPIE*, Vol. 4012, X-Ray Optics, Instruments, and Missions III, ed. Joachim E. Trümper, Bernd Aschenbach, p. 731-739
- Balucinska-Church, M., & McCammon, D. 1992, *ApJ*, 400, 699
- Berghöfer, T. W., Schmitt, J. H. M. M., Danner, R., & Cassinelli, J. P. 1997, *A&A*, 322, 167

- Cassinelli, J. P., Miller, N. A., Waldron, W. L., MacFarlane, J. J., & Cohen, D. H. 2001, *ApJ*, 554, L55
- Corcoran, M. F. 2005, *AJ*, 129, 2018
- Corcoran, M. F., Fredericks, A. C., Petre, R., Swank, J. H., & Drake, S. A. 2000, *ApJ*, 545, 420
- Corcoran, M. F., et al. 2004, *ApJ*, 613, 381
- Corcoran, M. F., Ishibashi, K., Davidson, K., Swank, J. H., Petre, R., & Schmitt, J. H. M. M. 1997, *Nature*, 390, 587
- Corcoran, M. F., Ishibashi, K., Swank, J. H., & Petre, R. 2001a, *ApJ*, 547, 1034
- Corcoran, M. F., et al. 1998, *ApJ*, 494, 381
- Corcoran, M. F., Rawley, G. L., Swank, J. H., & Petre, R. 1995, *ApJ*, 445, L121
- Corcoran, M. F., et al. 2001b, *ApJ*, 562, 1031
- Corcoran, M. F., et al. 1993, *ApJ*, 412, 792
- Cox, P., Mezger, P. G., Sievers, A., Najarro, F., Bronfman, L., Kreysa, E., & Haslam, G. 1995, *A&A*, 297, 168
- Damineli, A. 1996, *ApJ*, 460, L49
- Davidson, K. 1999, in *ASP Conf. Ser.* 179: *Eta Carinae at The Millennium*, ed. J. A. Morse, R. M. Humphreys, & A. Damineli, p. 304
- Davidson, K. 2002, in *Astronomical Society of the Pacific Conference Series*, p. 267
- Davidson, K., Dufour, R. J., Walborn, N. R., & Gull, T. R. 1984, in *IAU Symp. 105: Observational Tests of the Stellar Evolution Theory*, ed. A. Maeder & A. Renzini, 261
- Davidson, K., Ebbets, D., Weigelt, G., Humphreys, R. M., Hajian, A. R., Walborn, N. R., & Rosa, M. 1995, *AJ*, 109, 1784
- Davidson, K., & Humphreys, R. M. 1997, *ARA&A*, 35, 1
- Davidson, K., et al. 2005, *AJ*, 129, 900
- Davidson, K., Walborn, N. R., & Gull, T. R. 1982, *ApJ*, 254, L47
- den Herder, J. W., et al. 2001, *A&A*, 365, L7
- Duncan, R. A., White, S. M., Lim, J., Nelson, G. J., Drake, S. A., & Kundu, M. R. 1995, *ApJ*, 441, L73
- Evans, N. R., Seward, F. D., Krauss, M. I., Isobe, T., Nichols, J., Schlegel, E. M., & Wolk, S. J. 2003, *ApJ*, 589, 509
- Feast, M., Whitelock, P., & Marang, F. 2001, *MNRAS*, 322, 741
- Gayley, K. G., Owocki, S. P., & Cranmer, S. R. 1997, *ApJ*, 475, 786
- Hamaguchi, K., et al. 2006, *ArXiv Astrophysics e-prints* (astro-ph/0610024)
- Hillier, D. J., Davidson, K., Ishibashi, K., & Gull, T. 2001, *ApJ*, 553, 837
- Inoue, H. 1985, *Space Science Reviews*, 40, 317
- Ishibashi, K., Corcoran, M. F., Davidson, K., Swank, J. H., Petre, R., Drake, S. A., Damineli, A., & White, S. 1999, *ApJ*, 524, 983
- Ishibashi, K., et al. 2003, *AJ*, 125, 3222
- Ishida, M., Okada, S., Nakamura, R., Terada, Y., Mukai, K., & Hamaguchi, K. 2007, in *Proceedings of the Extreme Universe in the Suzaku Era, Progress of Theoretical Physics*, in preparation
- Jansen, F., et al. 2001, *A&A*, 365, L1
- Kahn, S. M., et al. 2001, *A&A*, 365, L312
- Kamata, Y., Koyama, K., Tsuboi, Y., & Yamauchi, S. 1997, *PASJ*, 49, 461
- Kitamoto, S., & Mukai, K. 1996, *PASJ*, 48, 813
- Kitamoto, S., Tanaka, S., Suzuki, T., Torii, K., Corcoran, M. F., & Waldron, W. 2000, *Advances in Space Research*, 25, 527
- Leutenegger, M. A., Kahn, S. M., & Ramsay, G. 2003, *ApJ*, 585, 1015
- Lotz, W. 1967, *ApJS*, 14, 207